Maintenance Scheduling of Power System Generating Units by Tabu Search

by

Mohammed Abbas Thadpatri

A Thesis Presented to the

FACULTY OF THE COLLEGE OF GRADUATE STUDIES

KING FAHD UNIVERSITY OF PETROLEUM & MINERALS

DHAHRAN, SAUDI ARABIA

In Partial Fulfillment of the
Requirements for the Degree of

MASTER OF SCIENCE

In

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COLLEGE OF GRADUATE STUDIES

Dedicated to my

Late Father *T. Abdul Sattar*

and

Mother *Sayeeda Begum*

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All praise is for Almighty Allah for having guided me at every stage of my life.

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Abstract

Name: Mohammed Abbas T.

Title: Maintenance Scheduling of Power System Generating Units by Tabu Search

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Maintenance Scheduling (MS) of generating units is an important aspect of long-term power systems planning. Maintenance schedules serve as an input to other important system planning tasks such as unit commitment, production costing and reliability calculations. Sub-optimal schedules can affect each of these tasks adversely. Therefore, it is imperative that optimal maintenance schedules are used. The MS problem is combinatorial in nature. Using exhaustive-search based optimal solution algorithms to schedule large number of generators may result in excessive computation. To obtain optimal maintenance schedules in a reasonable amount of time and with minimal computing resources, effective heuristic techniques are necessary. This thesis investigates the implementation of the heuristic technique of tabu search for solving the maintenance scheduling optimization problem. An improved maintenance scheduling optimization model is first formulated. Results obtained by the proposed tabu search method are compared with those of the zero-one implicit enumeration technique.

Master of Science Degree
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خلاصة الرسالة

اسم الطالب الكامل : محمد عباس تادبيتري

عنوان الرسالة : جدولة صيانة وحدات توليد الطاقة الكهربائية بطريقة المنع

التخصص : هندسة كهربائية .

تاريخ الشهادة : يونيو ١٩٩٥م .

تعتبر جدولة صيانة وحدات التوليد من الأمور الهامة في عملية التخطيط بعيد المدى وتكمن أهميتها في تأثيرها على اعتمادية نظم القوى الكهربائية وتكلفة الانتاج وانتاجية وحدات التوليد . لذلك فإنه من المهم جداً استخدام طرق مثالية لجدولة الصيانة ، ومن هذه الطرق المثالية طريقة البحث المستنفذ أو الشامل المثالية . إلاّ أن من مساوئها الوقت الطويل التي تتطلبه العمليات الحسابية . ومن أجل الحصول على جدولة مثالية وبوقت معقول وبأقل قدر من العمليات الحسابية فإنه ينبغي استخدام الطرق التنقيبية .

وتهدف هذه الرسالة إلى استخدام الطرق التنقيبية في بحث المنع للوصول إلى اسلوب مثالي لجدولة الصيانة .

في هذه الرسالة تم :

* عمل برنامج للحصول على جدولة الصيانة باستخدام طريقة التنقيبية .

* تم اعداد المعادلات اللازمة لتمثيل الموضوع بطريقة أفضل .

* تم مقارنة النتائج مع نتائج الاحصاء الضمي الرقمي .

درجة الماجستير في العلوم

جامعة الملك فهد للبترول والمعادن

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Nomenclature

I	number of generating units in the system.
i	an indexing variable representing various generating units, $1 \leq i \leq I$.
T	the set of all scheduling periods.
$\lvert T \rvert$	cardinal of T.
t	an indexing variable representing a equal scheduling period. $1 \leq t \leq T$.
E_i	earliest time (week) that maintenance on unit i can start.
L_i	latest time (week) that maintenance on unit i can start.
Y_i	set of all feasible starting periods for unit i, $Y_i = [E_i, \cdots, L_i]$.
y_i	maintenance start period of unit i, $y_i \in Y_i$.
M_i	duration of maintenance on unit i (in integral consecutive weeks).
MW	megawatt (unit of active power).
MWh	megawatt-hour (unit of energy).
R_i	the capacity of unit i (MW).
p_{it}	generator output (MW) of unit i in period t.
v_i	variable operation and maintenance cost for unit i in period t($/MWh).
F_{it}	generation cost for unit i in period t ($/hr).
a_i, b_i, c_i	fuel cost coefficients.
λ	equal incremental cost ($/MWh).
IC	total installed capacity (MW).

G_t	gross reserve (MW) available during $t\ th$ week.
N_t	net reserve (MW) available during the $t\ th$ week.
$\bar{N}$	(constant). average net reserve throughout the planning horizon.
R_{min}	minimum reserve kept for reliability considerations
D_t	peak load demand during the $t\ th$ week (MW).
x_{it}, z_{ik}	binary variables.
$LOLP$	loss of load probability.
MS	maintenance scheduling.
TS	tabu search.
MSP	maintenance start period.
$FIFO$	first-in first-out.
CS	current solution.

Chapter 1

Introduction

The increase in size and complexity of power systems during the last two decades has been accompanied with the fast development of automatic techniques and application software for solving system's operation and expansion problems. The necessity of implementing such techniques and the positive results obtained so far, make it superfluous to point at the need for their continuous improvement.

This thesis deals with results obtained by solving one of the typical power system long-term operation and planning problems -*preventive maintenance of thermal generating units* (henceforth: Maintenance Scheduling - MS).

The considerable impact of thermal units maintenance on the power system reliability and production costs has led to the utilization of advanced optimization techniques for scheduling generators for maintenance. As the number of thermal units and their participation in the total power system capacity continue to rise, the significance of optimal maintenance scheduling will continue to increase too.

1.1 Problem definition

Maintenance scheduling is a sub-problem of the long-term operations planning problem. The latter includes (a)long term hydro-thermal scheduling, (b)long term hydro scheduling, (c)interchange planning, and (d)fuel planning.

The definition presented in reference [1] states that long-term operations planning relates to the utilization and the maintenance of the power and energy resources during the period from several weeks in the future to several months or years beyond that time.

Other categories of power system operations planning are :

- short range operations planning(from several hours to one day or several weeks), and

- real time operation(second-by-second and minute-by-minute management).

Each classification is of course relative, however the purpose here is to accommodate the maintenance scheduling into an appropriate broader context.

The key words in the problem definition are *scheduling* and *maintenance*. However, it has to be emphasized that the main aspect of the problem is *scheduling*- of activities, manpower, resources etc in a manner leading to an optimal preventive maintenance of the power system.

The problem under consideration differs from typical problems of *production machine maintenance*, for which specific questions that have to be addressed are 'back order' and 'loss of sales'. The peculiarity of the maintenance scheduling of thermal generating units is a consequence of the following power system features:

- impracticality of storing the generated electrical energy.
- limited capability of the power transmission network.
- the need to ensure adequate amount of reserve.

The task of finding an optimal preventive maintenance schedule of thermal generating units can be stated as follows:

Define the time sequence of preventive maintenance outages for a given set of thermal generation units in a power system over a planning period, such that all the operating constraints are satisfied and the objectives are met.

1.2 Maintenance goals

The goals of preventive maintenance scheduling can be defined from three points of view: (a) intrinsic(technological), (b) power system, and (c) external(macro-economic and social).

1. From the technological point of view, the basic maintenance goals are:

- sustaining the characteristics of power generating equipment within acceptable limits;
- increasing the equipment reliability, i.e., reducing the probability of its outage caused by failure;
- improving the efficiency of operation;
- extending the working life of generating units.

The main maintenance activities which have to be carried out in order to achieve these goals are:

- preventive check-ups for all power generation components– boiler, turbine, generator and auxiliary equipment;
- repair or replacement of components whose working characteristics have fallen below acceptable limit due to wear and tear;
- cleaning and lubrication of moving parts.

2. From a power system's point of view, the maintenance goals are:

   - minimizing the fuel consumption and maintenance costs;
   - achieving the required power system reliability;

   A power system planning engineer is concerned with the objectives stated above. In order to achieve these, the engineer has to make a proper selection of the equipment characteristics. He/She also has to consider the suitability of the generation equipment for maintenance and the necessity for periodical preventive maintenance.

3. Finally, from an external standpoint, the maintenance goals are:
   - achieving the required security of supplying the consumers with electrical energy;
   - minimizing the cost of generated electrical energy;
   - postponing the investment into new generation facilities.

1.3 Importance of maintenance scheduling

Utilities spend billions of dollars per year for maintenance. The maintenance costs of fossil-fueled power plants in USA reached in the year 1986 four billion dollars [2]. The average maintenance costs for coal-fired plants vary between $13 and $15 per kilowatt [3]. The reliability of system operation and production cost is affected by the maintenance outage of generating facilities. Suboptimal maintenance schedules contribute to higher production cost and lower system reliability. The maintenance schedule affects many short and long-term planning functions. For example, unit commitment, fuel scheduling, reliability calculations and production costing all have a maintenance schedule as an input. A sub-optimal schedule could affect each of these functions adversely.

An optimal generator maintenance schedule increases system operating reliability, reduces generation cost, and extends generator lifetime. Additionally, optimized maintenance schedules could potentially defer some capital expenditure for new plants and allow critical maintenance work to be performed which might not otherwise be done. Therefore, maintenance scheduling in an electric utility is a significant part of the overall operations scheduling problem [4].

1.4 Basic features of the maintenance scheduling problem

The maintenance scheduling of thermal generation units is a large-scale combinatorial optimization problem with constraints. The number of independent variables in a mathematical model is determined by the number of units and by the number of time stages considered in the planning horizon. The astronomical number of possible maintenance schedules and the complexity of the constraints and objectives make the maintenance problem a difficult one. Only a few of these schedules will satisfy all the constraints. The optimal solution has to fulfill the requirements for system operation with minimal costs taking into account the imposed constraints [5].

1.5 Organisation of the thesis

The thesis contains a total of seven chapters. Chapter two contains the literature review and the thesis objectives. The mathematical formulation of the MS model used in the proposed work is presented in chapter three. Chapter four presents the implementation of the *tabu search* technique for solving the MS problem. In chapter five, the implementation of the zero-one integer program for solving the MS model is described. The tabu search and zero-one simulation results obtained are discussed in chapter six. Finally conclusions and suggestions for future work are given in chapter seven.

Chapter 2

Literature Review

In this chapter, the literature on maintenance scheduling is reviewed to reflect the general state-of-the-art.

2.1 Optimization techniques

Researchers, over the years have used the techniques of *dynamic programming*, *mixed integer programming*, and *integer programming* to solve the Maintenance Scheduling (MS) problem [5].

Linear programming, a fast and powerful optimization technique cannot be used to solve the MS problem. The main reason is that integer solutions are needed, and linear programming will attempt to schedule fractional outages. The appropriate approach to solving the MS problem is to use discrete optimization methods, which perform a systematic search through the solution space so that a great number of infeasible or inferior solutions are eliminated [5].

Theoretically, *Dynamic programming* (DP) is most suitable to the solution of MS problems because MS is a sequential decision process problem. However DP is severely limited by the *curse of dimensionality.* The curse of dimensionality states that a problem that is complex enough to be interesting is generally too large to be solved within practical constraints of computer time and storage. Methods that have been conceived as DP are invariably forced to resort to some sort of suboptimal approximations that reduce the dynamic programming solution to another heuristic [5].

Integer programming is a convenient method for solving various scheduling and resource allocation problems. This technique has been used by researchers to solve the MS problem [6]. However, the computational burden associated with integer programming motivated some authors to compromise with *mixed integer-linear programs.* Outages are grouped, with a few at a time restricted to integers. The rest are allowed to take on fractional values. Eventually, integer solutions are found for all outages. However, this is a sub-optimal approach. Optimality is not guaranteed, and a feasible schedule may not be found, even when there is one [5].

Expert systems use intuitively appealing rules-of-thumb to guide computer searches. They are typically 'fill in the valley' methods where the computer schedules the largest outage during the period of the highest net reserve, the second largest outage in the period having the next highest net reserve and so on. Maintenance schedules obtained using Expert systems are suboptimal. Only good working solutions can be obtained using Expert system approaches[7].

2.2 MS formulations

A thorough critical review of the MS literature is presented in [4]. The review shows that the existing methods, either make a lot of simplifications or solve a small problem.

Zurn and Quintana [8] formulated the MS problem to minimize the production cost. To make the problem manageable, they used a successive approximation approach in dynamic programming (DPSA) and grouped the units into small groups, whereby they reduced the state space. This approach, named by the authors as the group-sequential approach is a compromise between simultaneous and sequential maintenance scheduling.

Yamayee et.al [9] developed an MS model, defining the problem as a sequential decision process. The objective function in this model is formulated as a linear combination of reliability and production costs. The DPSA technique is used in finding the optimal solution.

Garver [10] introduced the 'levelized risk' method to include load uncertainties and forced outages of generating units in the problem formulation. The constraints considered were the resource and crew constraints. The levelized risk method has a random reliability objective function. The objective is to make the risk more or less the same throughout the planning horizon being considered. The Loss of Load Probability (LOLP) reliability index is used to evaluate the system risk and as a result, the levelized risk principle can be expressed as $LOLP_i = LOLP_j,\ j\epsilon t,\ t = 1, 2, 3.......T$ in which $LOLP_i$ and $LOLP_j$ are the system risk in any stage and 'T' is the number of stages in the maintenance period.

Garver [10] did not consider the effect of taking a unit out for maintenance because of excessive computations. Later, Stremel [11] overcame this problem by using the method of cumulants, but he did not consider load uncertainties. In a separate paper, Stremel and Jenkins [12] incorporated the effect of load uncertainty in the problem formulation.

Patton and Ali [13] presented the 'Annual risk minimization' method. This method, which is an extension of the 'levelized risk' method avoids the usage of effective load carrying capability of units. Units are scheduled for maintenance in such a way that the LOLP is minimized.

Many other stochastic reliability objectives have been presented, such as Interruption Duration Index [14], Expected Unsupplied Energy and others [15]. It should be emphasized that all stochastic approaches have used heuristics of some kind to reduce the computational efforts.

Dopazo and Merrill [6] formulated the maintenance problem as a zero-one integer linear program. The zero-one integer model of Dopazo and Merrill is among the first attempts to formulate the MS problem as a discrete optimization task. This solution method is based on the implicit enumeration algorithm of Balas. The constraints considered in the model were capacity and sequence constraints. The solution procedure minimized the maintenance costs only. The system reliability aspects were ignored in the problem formulation.

Escudero et al. [16] formulated the MS problem as a mixed-integer linear programming task. Three alternate objectives were considered namely maximizing the minimum net reserve, levelizing the reserve and minimizing the deviation of the maintenance schedule from the ideal schedule (obtained from the preferred maintenance beginning periods of each generator). The constraints considered in the formulation include resource, demand, and precedence constraints. A combination of implicit enumeration and branch-and-bound techniques was used in solving the problem.

Contaxis et.al [17] proposed a method that evaluates the risk level of a power system and then performs maintenance scheduling of generating units. The minimization of the annual system risk was the objective considered in the problem formulation.

Chen and Toyada [18] proposed an MS method to equalize incremental risk, such as the loss of load probability (LOLP) throughout the year. They adopted a new approach based on a two level hierarchical structure model in order to simplify the combinatorial problem and optimize the maintenance scheduling. The proposed algorithm was applied to a practical example of nineteen generators.

Mukerji & Parker [5] formulated the MS problem as zero-one program. The optimization criteria considered were maximizing reliability and minimization of the production cost. Constraints such as resource, precedence, and crew constraints were considered in the problem formulation.

Yellen et.al [19] demonstrated the applicability of the Decomposition approach for the purposes of maintenance scheduling. In [19], the total operating costs over the operational planning period of a power system were minimized subject to unit maintenance and system constraints. Load and reliability constitute the system constraints whereas the unit maintenance constraints include crew, reserve, and maintenance completion. The paper [19] presents the results of unit maintenance scheduling based on the duality theory. In the first stage, a master problem (essentially a 0-1 integer program) is solved to determine a trial solution for the maintenance scheduling decision variables. In the second stage, a subproblem calculates the minimum operating cost while satisfying the reliability constraints for each week of the study period. New constraints for the master problem are generated from the solution of the subproblem using the duality theory, so that an improved maintenance schedule may be obtained. The procedure is continued until an optimal or near-optimal solution is found.

Al-Khamis et.al [20] extended the work of Yellen et.al [19] to include unit fuel constraints in the problem formulation. The MS problem was solved using the Decomposition approach described above.

Satoh and Nara [21] formulated the MS problem as a mixed-integer programming problem and solved it using the heuristic method of simulated annealing. The simulated annealing method assumes an analogy between the physical annealing process of a metal and the problem of solving large combinatorial optimization problem. The simulated annealing method derives inspiration from the process of carefully cooling molten metals in order to obtain a good crystal structure. During the annealing process, a metal is heated to a high temperature and is then slowly cooled. By cooling the metal at a proper rate, the atoms will have an increased chance to regain proper crystal structure. If optimization is compared to the annealing process, the attainment of a global optimum is analogous to the attainment of a good crystal structure [22]. In the simulated annealing method, the following two equivalences are assumed:

1. Solutions of a combinatorial optimization problem are equivalent to states (arrangement of atoms) of a physical system.

2. The cost of a solution is equivalent to the energy of the state.

The temperature of the physical system is treated as a control parameter and a new solution is generated through a neighborhood structure and a generation mechanism. The numerical results obtained in [21] show that the proposed method could be applicable to a realistic power system.

Lin et.al [23] proposed a prototype maintenance scheduling expert system. The knowledge base for the expert system includes generator constraints and expert experience . An Operation index was proposed to determine an appropriate strategy for decision-making process.

Kralj and Rajakovic [24] proposed a multiobjective optimization model for solving the MS problem. The following objectives are simultaneously considered : power system reliability maximization, fuel costs minimization and minimization of constraints violations. The proposed model is based on the original multiobjective branch and bound algorithm.

2.3 Scope of the work

The combinatorial nature of the MS problem makes it suitable to use the heuristic solution technique called *tabu search.* Prior to commencement of this work, no one has attempted to implement the technique of tabu search for solving the MS problem. This thesis presents the results obtained from applying the new solution strategy of tabu search to the maintenance scheduling optimization problem.

In this study, a generalized optimization model for maintenance scheduling of generating units is developed first. The tabu search technique is implemented for solving the MS model. The MS model is also solved by using the existing zero-one additive algorithm and the results obtained are compared with the tabu search results.

Chapter 3

Optimization Model

This chapter presents the formulation of the maintenance scheduling optimization model.

3.1 Problem statement

Maintenance Scheduling involves specifying the optimal periods on which the generators in a power system should be committed for maintenance. The maintenance starting periods should satisfy the operating/planning constraints and meet the objective criteria.

The proposed optimization model requires the following data as input for scheduling the power system generators for maintenance.

1. The total number of weeks in the planning horizon.

2. The total number of generators, their maintenance durations and their earliest and latest maintenance starting periods.
3. The total installed capacity in the power system.
4. Weekly peak load forecast data.
5. The minimum reserve that should be kept for reliability considerations.
6. The data related to the crew and precedence constraints.
7. The operating cost data i.e., the variable operating and maintenance costs and fuel cost coefficients for the various generating units in the power system.

3.2 Constraints in the MS model

In the proposed MS optimization model, the following constraints are considered.

3.2.1 Maintenance completion constraints

The maintenance completion constraint ensures that once a unit is removed from the system for maintenance, it completes the maintenance without interruption and that it does so in a time period which is exactly equal to it's maintenance duration of M_i weeks. The maintenance completion constraint also ensures that a unit is maintained just once during the planning horizon.

Let,

I : Total number of units in the system.

T : Length of the maintenance planning horizon.

E_i : Earliest time (week) that maintenance on unit i can start.

L_i : Latest time (week) that maintenance on unit i can start.

$[E_i, \cdots, L_i]$: Maintenance window for unit i.

M_i : Maintenance duration of unit i.

$$\text{Let} \qquad z_{ik} = \begin{cases} 1 & \text{if unit } i \text{ begins maintenance in the } k \text{ th week} \\ 0 & \text{else where} \end{cases} \tag{3.1}$$

where $k \in [E_i, \cdots, L_i]$ and $i = 1, \cdots, I$.

Since a unit i has to begin maintenance just once during the planning horizon, we have

$$\sum_{k=E_i}^{L_i} z_{ik} = 1, \quad i = 1, \cdots, I \tag{3.2}$$

$$\text{Let} \qquad x_{it} = \begin{cases} 1 & \forall \;\; t = k, \cdots, k + M_i - 1 \\ 0 & \text{else where.} \;\; E_i \leq t < k; \quad (k + M_i - 1) < t \leq L_i \end{cases} \tag{3.3}$$

To ensure that an unit i is in the maintenance state for just M_i consecutive periods, we have the following equation:

$$\sum_{t=k}^{k+M_i-1} x_{it} = M_i, \quad i = 1, \cdots, I \qquad E_i \leq k \leq L_i \tag{3.4}$$

The maintenance completion constraint can be expressed as :

$$(1 - z_{ik})Q \geq \left[\sum_{t=k}^{k+M_i-1} x_{it} - M_i \right] \geq (z_{ik} - 1)Q \tag{3.5}$$

$$\sum_{k=E_i}^{L_i} z_{ik} = 1 \quad i = 1, \cdots, I; \quad E_i \leq k \leq L_i$$

where Q is a large number.

3.2.2 Crew Constraints

The crew constraints depend on the manpower that is available and specify that no two units can be simultaneously maintained by the same crew.

Let units $i1$ and $i2$ have a single maintenance crew assigned to them. As a result, the crew can carry out maintenance work on only one generating unit at any stage in the planning horizon. Both units $i1$ and $i2$ cannot be maintained at the same time. Let $i1$ be the unit having the larger maintenance duration and $i2$ be the unit with the smaller maintenance duration ($M_{i1} > M_{i2}$). The equation given below ensures that unit $i2$ is not in the maintenance state for a period equal to the maintenance duration M_{i1} of the first unit:

$$\sum_{t=k}^{k+M_{i1}-1} x_{i2,t} = 0 \tag{3.6}$$

$$E_{i1} \leq k \leq L_{i1}$$

The crew constraint is expressed in terms of the x_{it} variables of the second unit $i2$ as follows:

$$(1 - z_{i1,k})Q \geq \left[\sum_{t=k}^{k+M_{i1}-1} x_{i2,t} - 0\right] \geq (z_{i1,k} - 1)Q \tag{3.7}$$

$$E_{i1} \leq k \leq L_{i1}$$

3.2.3 Precedence constraints

There are situations wherein it is required to maintain the most critical generating unit first before committing the other units in the system for maintenance. The proposed MS model handles this requirement using the Precedence constraints. The Precedence constraint specifies the order in which the maintenance on the units have to be performed.

Let unit $i1$ be maintained before unit $i2$. In other words, unit $i2$ can be committed for maintenance only after the maintenance on unit $i1$ has been completed. To ensure that this scenario takes place, the following equation written in terms of the x_{it} variables of the second unit $i2$ is considered:

$$\sum_{t=E_{i2}}^{k-1} x_{i2,t} + \sum_{t=k}^{k+M_{i1}-1} x_{i2,t} = 0 \tag{3.8}$$

$$E_{i1} \leq k \leq L_{i1}$$

The first term in the above equation ensures that unit $i2$ is not in the maintenance state *before* unit $i1$ begins maintenance. The second term ensures that unit $i2$ can commence maintenance only *after* unit $i1$ has completed maintenance.

The Precedence constraint can be expressed as follows:

$$(1 - z_{i1,k})Q \geq \left[(\sum_{t=E_{i2}}^{k-1} x_{i2,t} + \sum_{t=k}^{k+M_{i1}-1} x_{i2,t}) - 0 \right] \geq (z_{i1,k} - 1)Q \tag{3.9}$$

$$E_{i1} \leq k \leq L_{i1}$$

3.2.4 Resource constraints

The Resource or the Capacity constraint ensures that the maintenance outage capacity does not exceed the gross reserve during any stage of maintenance.

$$\sum_{t=1}^{T} x_{it} \ R_i \leq G_t \qquad i = 1, \ldots, I. \tag{3.10}$$

where

R_i: Rating of unit i.

D_t: Forecasted peak demand in period t.

IC: Installed capacity $= \sum_{i=1}^{I} R_i$

G_t: Gross reserve in period $t = IC - D_t$

T: Planning horizon.

3.2.5 Reserve constraints

In order to ensure that the total available power is greater than the demand even when a random outage of one unit occurs, the reserve constraints are imposed. i.e., the total available power from the units which are not committed to maintenance must be greater than the demand plus the reserve.

$$\sum_{i=1}^{I} R_i(1 - x_{it}) \geq D_t + R_{min} \quad t = 1, \cdots, T \tag{3.11}$$

where

D_t : Peak load demand in period t.

R_i : Rating of unit i (MW).

R_{min} : Minimum reserve kept in the power system for reliability considerations. The value of this minimum reserve requirement may be decided on the basis of : (1) size of the largest generating unit in the system, (2) constant percentage of the peak demand.

3.3 Objective criteria of the proposed MS optimization model

The objective criteria seek to maximize the power system reliability and minimize the total generator operating cost over the overall planning horizon.

3.3.1 Minimizing the total generator operating cost

Choosing a maintenance schedule which minimizes generator operating costs is often the foremost consideration of electric utilities. The proposed maintenance scheduling (MS) optimization model seeks to minimize the total generator operating cost over the operational planning period.

The generator operating cost has two main components namely energy production cost and maintenance cost. The energy production cost is the major component of a generating unit's operating cost. It is the cost of burnt fuel for producing a given amount of electric energy. Maintenance cost in the context of long-term operation scheduling planning, consists of two components. The first one is a fixed maintenance cost which is required for a generating facility regardless of how often or how long the facility is used to generate electric energy. This component is usually given as a constant for a given unit. The second component is the variable operation and maintenance (O & M) cost and is dependent upon the usage of the generating unit. Normally this O & M cost is given in dollars per - unit energy produced. This cost includes wear and tear due to frequency of startup's and shutdowns, the duration and level of operation of the generating facility etc.

Let,

λ : incremental cost in $\$/MWh$.

p_{it} : generator output (MW) of unit i in period t. This is computed based on the criterion of equal incremental cost λ (see appendix).

a_i, b_i, c_i : fuel cost coefficients.

v_i : variable O & M cost for unit i in \$/MWh.

168 : number of hours in a week.

The objective function for minimizing the total generator operating cost over the planning horizon can be stated as:

$$\text{Min } \sum_{i=1}^{I}\sum_{t=1}^{T} 168(a_i + b_i p_{it} + c_i p_{it}^2)(1 - x_{it}) + \sum_{i=1}^{I}\sum_{t=1}^{T} 168 p_{it} v_i (1 - x_{it}) \tag{3.12}$$

3.3.2 Levelling the reserve

The reliability consideration in the MS model is addressed by 'levelling the net reserve'. It consists of minimizing the deviation of the net reserve from the average net reserve $\bar{N}$. $\bar{N}$ being constant, the objective is to obtain a maintenance schedule so that the net reserve N_t in each scheduling period be as close as possible to the ideal net reserve $\bar{N}$. Thus the overall risk of any contingency is minimized.

Let,

D_t : Peak load demand in period t

IC : Installed capacity = $\sum_{i=1}^{I} R_i$

G_t : Gross reserve in period $t = IC - D_t$

M_i : Maintenance duration of unit i

N_t : Net reserve in period t= Gross reserve in period t - Maintenance outage capacity in period t.

$\bar{N}$: Average net reserve

The average net reserve is:

$$\bar{N} = \sum_{t=1}^{T} N_t/|T| \tag{3.13}$$

Where,

$$\sum_{t=1}^{T} N_t = \sum_{t=1}^{T} G_t - \sum_{i=1}^{I} R_i M_i \tag{3.14}$$

Therefore,

$$\bar{N} = \left[\sum_{t=1}^{T} G_t - \sum_{t=1}^{T} \sum_{i=1}^{I} R_i \ M_i\right] /|T| \tag{3.15}$$

$$N_t = G_t - \sum_{i=1}^{I} R_i x_{it} \tag{3.16}$$

'Levelling the reserve' can be stated as follows:

Minimize the deviation of the net reserve from the average net reserve i.e.,

$$\text{Min} \ \sum_{t=1}^{T} \bar{N} - N_t \tag{3.17}$$

3.4 Illustration

The development of the MS optimization model is illustrated by considering a power system having 4-units. Each one of these units have to be scheduled for maintenance just once during a planning horizon of 8 weeks. The forecasted weekly peak demands and other relevant details for the 4 units are listed in the tables 3.1 and 3.2 respectively.

For the given problem,

I : Total number of units = 4

T : Number of weeks in the planning horizon = 8

IC : Total installed capacity = 790 MW.

Maintenance completion constraints

Unit 1

E_1=1, L_1=5 and M_1=4 weeks

Unit No.1 has 5 possible starting periods $(E_1 + L_1 - 1)$. For each of the possible starting times, the following decision variables z_{11}, z_{12}, z_{13}, z_{14} and z_{15} are associated. For example, if unit 1 begins maintenance in week 1, then only $z_{11} = 1$ and the rest are all equal to zero. Unit 1 will be out of the system for a period equal to its maintenance duration M_1 of 4 weeks. This is indicated by the elevation of the binary variables x_{11}, x_{12}, x_{13} and x_{14} to the value 1.

We have for unit 1, the following constraints:

$$\left.\begin{aligned}
(1-z_{11})Q &\geq [x_{11}+x_{12}+x_{13}+x_{14}-4] &&\geq (z_{11}-1)Q \\
(1-z_{12})Q &\geq [x_{12}+x_{13}+x_{14}+x_{15}-4] &&\geq (z_{12}-1)Q \\
(1-z_{13})Q &\geq [x_{13}+x_{14}+x_{15}+x_{16}-4] &&\geq (z_{13}-1)Q \\
(1-z_{14})Q &\geq [x_{14}+x_{15}+x_{16}+x_{17}-4] &&\geq (z_{14}-1)Q \\
(1-z_{15})Q &\geq [x_{15}+x_{16}+x_{17}+x_{18}-4] &&\geq (z_{15}-1)Q
\end{aligned}\right\} \tag{3.18}$$

Table 3.1: 4-Unit problem data

i	R_i	E_i	L_i	M_i	a	b	c	v_i
1	200	1	5	4	78	7.97	0.00482	0.2
2	200	1	7	2	80	7.80	0.00462	0.2
4	300	1	7	2	110	7.65	0.00465	0.4
4	90	1	8	1	60	8.40	0.00610	0.5

Table 3.2: Weekly peak load and gross reserves

t	D_t	G_t
1	249	541
2	265	525
4	276	514
4	279	511
5	256	534
6	307	483
7	187	603
8	295	495

Out of the 5 possible combinations listed above for unit 1, only one should be active during the planning horizon. This is ensured by the following constraint.

$$z_{11} + z_{12} + z_{13} + z_{14} + z_{15} = 1 \tag{3.19}$$

The constraint given above also ensures that unit 1 is maintained just once during the planning horizon.

Unit 2

E_2=1, L_2=5 and M_2=2 weeks

Unit 2 has 7 possible starting periods $(E_2 + L_2 - 1)$. For each of the possible starting times, the following decision variables z_{21}, z_{22}, z_{24}, z_{24}, z_{25}, z_{26} and z_{27} are associated. For example, if unit 2 begins maintenance in week 5, then $z_{25} = 1$ and the unit will be out of the system for a period equal to its maintenance duration M_2 of 2 weeks. This is indicated by the elevation of the corresponding binary variables x_{25} and x_{26} to the value 1.

We have for unit 2, the following constraints:

$$\left.\begin{aligned}
(1-z_{21})Q &\geq [x_{21}+x_{22}-2] \geq (z_{21}-1)Q \\
(1-z_{22})Q &\geq [x_{22}+x_{23}-2] \geq (z_{22}-1)Q \\
(1-z_{23})Q &\geq [x_{23}+x_{24}-2] \geq (z_{23}-1)Q \\
(1-z_{24})Q &\geq [x_{24}+x_{25}-2] \geq (z_{24}-1)Q \\
(1-z_{25})Q &\geq [x_{25}+x_{26}-2] \geq (z_{25}-1)Q \\
(1-z_{26})Q &\geq [x_{26}+x_{27}-2] \geq (z_{26}-1)Q \\
(1-z_{27})Q &\geq [x_{27}+x_{28}-2] \geq (z_{27}-1)Q
\end{aligned}\right\} \tag{3.20}$$

The constraint

$$z_{21}+z_{22}+z_{24}+z_{24}+z_{25}+z_{26}+z_{27}=1 \tag{3.21}$$

ensures the selection of just one of the seven possible combinations for unit 2.

The maintenance completion constraints for units 3 & 4 can be written in a similar fashion.

Unit 3

E_3=1, L_3=7 and M_3=2 weeks

$$\left.\begin{array}{lll}(1-z_{31})Q & \geq [x_{31}+x_{32}-2] & \geq (z_{31}-1)Q \\ (1-z_{32})Q & \geq [x_{32}+x_{33}-2] & \geq (z_{32}-1)Q \\ (1-z_{33})Q & \geq [x_{33}+x_{34}-2] & \geq (z_{33}-1)Q \\ (1-z_{34})Q & \geq [x_{34}+x_{35}-2] & \geq (z_{34}-1)Q \\ (1-z_{35})Q & \geq [x_{35}+x_{36}-2] & \geq (z_{35}-1)Q \\ (1-z_{36})Q & \geq [x_{36}+x_{37}-2] & \geq (z_{36}-1)Q \\ (1-z_{37})Q & \geq [x_{37}+x_{38}-2] & \geq (z_{37}-1)Q \end{array}\right\} \tag{3.22}$$

The constraint

$$z_{31}+z_{32}+z_{34}+z_{34}+z_{35}+z_{36}+z_{37}=1 \tag{3.23}$$

ensures the selection of just one of the seven possible maintenance constraint combinations for unit 3.

Unit 4

E_4=1, L_4=8 and M_4=1 week

The maintenance completion constraints for unit 4 are :

$$\left.\begin{aligned}
(1-z_{41})Q &\geq [x_{41}-1] \geq (z_{41}-1)Q \\
(1-z_{42})Q &\geq [x_{42}-1] \geq (z_{44}-1)Q \\
(1-z_{43})Q &\geq [x_{43}-1] \geq (z_{43}-1)Q \\
(1-z_{44})Q &\geq [x_{44}-1] \geq (z_{44}-1)Q \\
(1-z_{45})Q &\geq [x_{45}-1] \geq (z_{45}-1)Q \\
(1-z_{46})Q &\geq [x_{46}-1] \geq (z_{46}-1)Q \\
(1-z_{47})Q &\geq [x_{47}-1] \geq (z_{47}-1)Q \\
(1-z_{48})Q &\geq [x_{48}-1] \geq (z_{48}-1)Q
\end{aligned}\right\} \tag{3.24}$$

The constraint

$$z_{41}+z_{42}+z_{43}+z_{44}+z_{45}+z_{46}+z_{47}+z_{48}=1 \tag{3.25}$$

ensures the selection of just one of the eight possible maintenance constraint combinations for unit 4.

Crew constraint

A single maintenance crew is assigned for maintaining units 1 & 2. As a result, units 1 & 2 cannot be committed for maintenance simultaneously at any stage during the planning horizon.

The maintenance duration of unit 1 is greater than that of unit 2. As per the formulation, the crew constraint is expressed in terms of the x_{it} variables of unit 2 as follows:

$$\left.\begin{array}{lll}(1-z_{11})Q & \geq [x_{21}+x_{22}+x_{23}+x_{24}-0] & \geq (z_{11}-1)Q \\ (1-z_{12})Q & \geq [x_{22}+x_{23}+x_{24}+x_{25}-0] & \geq (z_{12}-1)Q \\ (1-z_{13})Q & \geq [x_{23}+x_{24}+x_{25}+x_{26}-0] & \geq (z_{13}-1)Q \\ (1-z_{14})Q & \geq [x_{24}+x_{25}+x_{26}+x_{27}-0] & \geq (z_{14}-1)Q \\ (1-z_{15})Q & \geq [x_{25}+x_{26}+x_{27}+x_{28}-0] & \geq (z_{15}-1)Q\end{array}\right\} \quad (3.26)$$

Equation 3.19 will ensure the selection of just one of the 5 possible crew constraint combinations listed above for the given planning horizon.

Precedence constraint

The Precedence constraint for the given problem is that unit 1 should be maintained before unit 2. In other words, unit 2 can be committed for maintenance only after the maintenance of unit 1 has been completed. Since unit 2 has the lesser maintenance duration compared to unit 1, the required precedence constraint is expressed in terms of the x_{it} variables of unit 2.

$$\left.\begin{array}{lcl}(1-z_{11})Q & \geq [x_{21}+x_{22}+x_{23}+x_{24}-0] & \geq (z_{11}-1)Q \\ (1-z_{12})Q & \geq [x_{21}+x_{22}+x_{23}+x_{24}+x_{25}-0] & \geq (z_{12}-1)Q \\ (1-z_{13})Q & \geq [x_{21}+x_{22}+x_{23}+x_{24}+x_{25}+x_{26}-0] & \geq (z_{13}-1)Q \\ (1-z_{14})Q & \geq [x_{21}+x_{22}+x_{23}+x_{24}+x_{25}+x_{26}+x_{27}-0] & \geq (z_{14}-1)Q \\ (1-z_{15})Q & \geq [x_{21}+x_{22}+x_{23}+x_{24}+x_{25}+x_{26}+x_{27}+x_{28}-0] & \geq (z_{15}-1)Q\end{array}\right\} \quad (3.27)$$

Equation 3.19 will ensure the selection of just one of the 5 possible precedence constraint combinations listed above for the given planning horizon.

Resource constraints

$$\sum_{i=1}^{I} x_{it} \ R_i \leq G_t \quad t = 1, \ldots, T. \tag{3.28}$$

$$\left.\begin{aligned}
200x_{11} + 200x_{21} + 300x_{31} + 90x_{41} &\leq 541 \\
200x_{12} + 200x_{22} + 300x_{32} + 90x_{42} &\leq 525 \\
200x_{13} + 200x_{23} + 300x_{33} + 90x_{43} &\leq 514 \\
200x_{14} + 200x_{24} + 300x_{34} + 90x_{44} &\leq 511 \\
200x_{15} + 200x_{25} + 300x_{35} + 90x_{45} &\leq 534 \\
200x_{16} + 200x_{26} + 300x_{36} + 90x_{46} &\leq 483 \\
200x_{17} + 200x_{27} + 300x_{37} + 90x_{47} &\leq 603 \\
200x_{18} + 200x_{28} + 300x_{38} + 90x_{48} &\leq 495
\end{aligned}\right\} \tag{3.29}$$

Reserve constraints

$$\sum_{i=1}^{I} R_i(1 - x_{it}) \geq D_t + R_{min} \quad t = 1, \cdots, T \tag{3.30}$$

For the given problem, a reserve equal to 20 % of the maximum weekly peak demand is kept for reliability considerations.

Maximum $(D_t) = 307$ MW.

$R_{min} = 0.20(307) = 62$ MW.

The reserve constraints ensure that the the total available power from units which are not committed to maintenance is greater than the demand plus the reserve.

$$\left.\begin{array}{l}
200(1-x_{11})+200(1-x_{21})+300(1-x_{31})+90(1-x_{41})\geq 311\\
200(1-x_{12})+200(1-x_{22})+300(1-x_{32})+90(1-x_{42})\geq 327\\
200(1-x_{13})+200(1-x_{23})+300(1-x_{33})+90(1-x_{43})\geq 338\\
200(1-x_{14})+200(1-x_{24})+300(1-x_{34})+90(1-x_{44})\geq 341\\
200(1-x_{15})+200(1-x_{25})+300(1-x_{35})+90(1-x_{45})\geq 318\\
200(1-x_{16})+200(1-x_{26})+300(1-x_{36})+90(1-x_{46})\geq 369\\
200(1-x_{17})+200(1-x_{27})+300(1-x_{37})+90(1-x_{47})\geq 249\\
200(1-x_{18})+200(1-x_{28})+300(1-x_{38})+90(1-x_{48})\geq 357
\end{array}\right\} \tag{3.31}$$

3.5 Concluding remarks

From the illustration of the problem formulation for the 4-unit example, it is evident that an MS optimization model will have a large number of binary variables and constraints. The number of binary variables (z_{ik} and x_{it}) that are required depend on the following factors:

- The total number of weeks in the maintenance planning horizon.
- The total number of generators present in the system.
- The specified maintenance window limits i.e., the earliest and latest maintenance starting periods of the generators.

In the illustrative example of the 4-units, there are a total of 59 binary variables. Out of these, 27 z_{ik} variables were needed to specify all the possible maintenance starting periods of the 4 generators in the system. The number of z_{ik} variables that are needed depend on the specified generator maintenance window limits. A total of 32 x_{it} variables are needed to represent whether the 4 generators are in the maintenance state or not during the 8 week maintenance planning horizon.

Typically, power systems have a large number of generators and these will have to be scheduled for maintenance over a planning horizon of 52 weeks. The maintenance window limits for the units are also usually large. All these will result in a large size problem.

The maintenance scheduling problem is a combinatorial optimization problem. Optimal solution algorithms such as integer programming can be used to solve the MS problem. However, scheduling large number of generators using exhaustive search-based techniques may result in excessive computation. Heuristic algorithms are therefore worth developing. A solution strategy based on the heuristic technique of *tabu search* is suitable because of the combinatorial nature of the MS problem. The implementation of the tabu search strategy is presented in chapter 4.

Chapter 4

Tabu Search

In this chapter, the general tabu search technique is presented, followed by it's implementation details for solving the maintenance scheduling optimization model.

4.1 General framework

Tabu Search (TS) was originally proposed as an optimization tool by Glover in 1977 [25]. TS is a conceptually simple and elegant iterative technique for finding good solutions to combinatorial optimization problems. In general terms, TS is an iterative improvement procedure in that it starts from some initial feasible solution and attempts to determine a better solution in the manner of a greatest descent algorithm. The salient feature of TS is it's ability to escape local optima. This is achieved by using a short-term memory of recent solutions called the *tabu list*. Moreover, tabu search permits backtracking to previous solutions by using the *aspiration criteria.* This backtracking may ultimately lead the search, via a different direction, to better solutions [26]. The features of a tabu list and aspiration criteria make tabu search a powerful optimization tool. Tabu search has proven itself to be very useful in providing good solutions for many problems in a reasonable amount of time. Examples include machine scheduling, employee scheduling, character recognition, telecommunications path assignment, quadratic assignment problems, graph coloring and partitioning problems, traveling salesman problems [25], VLSI placement [27] etc.

4.1.1 Tabu Restrictions

Tabu search goes from one trial solution to another by making moves. It makes several candidate moves and selects the move producing the best solution among all candidate moves for the current iteration. The set of admissible moves forms a *candidate list.* The best candidate solution becomes the current solution. It is possible that the tabu search may visit the same solution again in latter iterations. Thus there is a possibility of cycling. Tabu restriction is a means to avoid such cycling by making the current solution *tabu* i.e., forbidden. Tabu restrictions are enforced by a *tabu list.* The tabu list is a list containing forbidden moves (solutions). It is forbidden to accept the same solution as long as it is in the tabu list. Tabu restrictions allow the search to go beyond the points of local optimality while still making the best possible move in each iteration. The tabu list is initially empty, constructed in the first s iterations and updated in latter iterations. The parameter s is called the *tabu list size.* The tabu list ensures that the tabu search avoids returning to the solutions just visited and since degrading moves are allowed, the tabu search algorithm has a chance of leaving a local minimum [23].

The most difficult part in applying tabu search is finding the right tabu list size. No single rule gives good sizes for all classes of problems. If the tabu list size is too small, the search process may start cycling and if it is too large, the search may be too restrictive. Therefore, an appropriate list size has to be determined by noting the occurrence of cycling when the size is too small and the quality of the solution when the size is too large. It is a matter of arriving at the right compromise depending upon the problem being investigated [28]. Several applications of tabu search that have employed tabu conditions have found the *magic number* 7 (± 2) to be a remarkably good choice for tabu list size [23].

4.1.2 Aspiration criterion

The Aspiration criterion is usually introduced to speed up the tabu search process. The aspiration criterion temporarily overrides the tabu status of a move if it is sufficiently good. The simplest aspiration criterion is to override the tabu status of a move and allow it into the tabu list if it leads to a better solution than the best obtained thus far [23].

4.1.3 Working of a simple tabu search

A simplified description of a typical tabu search technique is illustrated in Fig. 4.1. The tabu search starts with an initial solution. The initial solution is also assumed to be the current best solution. The current solution is perturbed with moves to generate a new set of trial solutions. Each move generates a trial solution. The number of moves to be made depends on the problem being considered. The move that generates the best solution among the set of trial solutions is selected. This move called the *candidate move* is checked to see if it is tabu. If is is not in the tabu list, it becomes the current solution. If the candidate solution is found to be tabu, its aspiration criterion is checked. If it passes the aspiration criterion, then it becomes the current best solution, otherwise moves are regenerated to get another set of new solutions and the process is repeated. The tabu search is terminated as soon as the stopping criteria are satisfied [29].

4.2 Tabu search implementation for the maintenance scheduling of generators

The aim of maintenance scheduling is to find the optimal maintenance start periods of the various generating units in the system. In this work, the optimization is accomplished by using the tabu search method. The new tabu search strategy which

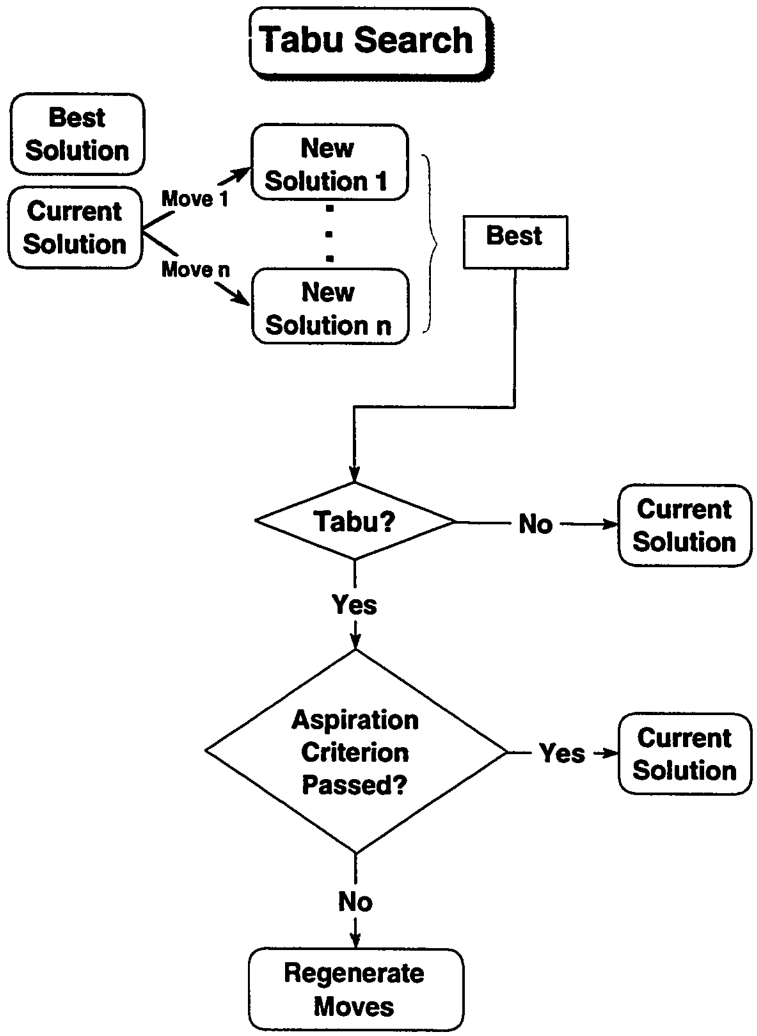

Figure 4.1: Tabu search

was developed to solve the maintenance scheduling problem is described below.

4.2.1 Salient features

Separate tabu lists are kept for each generating unit in the tabu search implementation. The size of these tabu lists are arrived at based on the maintenance window limits (i.e., earliest & latest starting times). The entries into the tabu lists are the actual maintenance starting times of the units.

The aspiration criterion used in the implementation is to override the tabu status of a tabu solution if it results in a better objective function value than the best obtained thus far.

The stopping criteria used in the implementation is to terminate the solution process if no improvement is seen in the cost for a predefined number of steps or if the number of iterations exceed the maximum count.

4.2.2 Algorithmic description

The proposed tabu search implementation is illustrated in figures 4.2 and 4.3. The various steps in the proposed tabu search solution strategy are described below:

1. Read in the problem data. Initialize the tabu lists and the iteration counter.

2. Generate randomly the values of the maintenance starting periods (MSP) of the generators from their respective maintenance windows i.e., $\{z_{ik}; k \in$

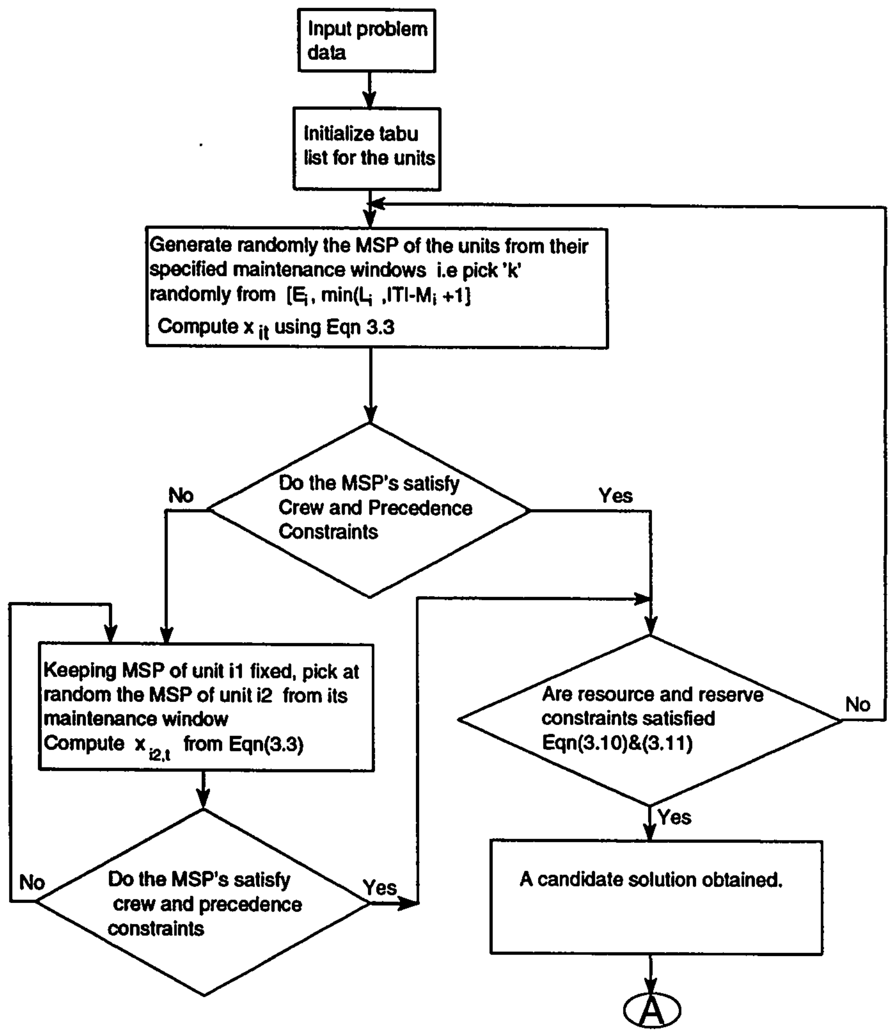

Figure 4.2: Tabu search implementation for the maintenance scheduling problem (continued)

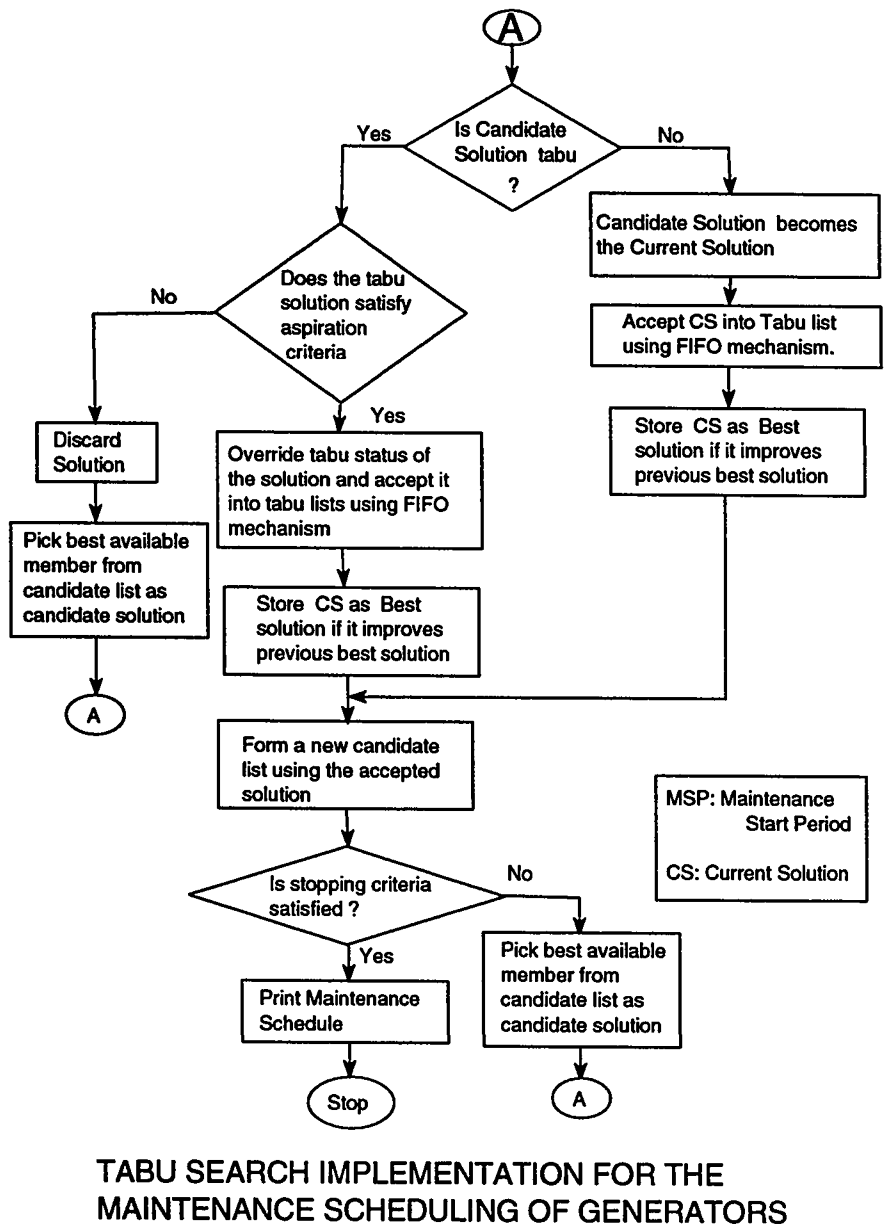

Figure 4.3: Tabu search implementation for the maintenance scheduling problem

$[E_i, \cdots, L_i]$, $, i = 1, \cdots, I$ }. Based on the z_{ik} values, compute the corresponding x_{it} values using equation 3.3.

3. Check whether the generated MSP i.e., the z_{ik} and the corresponding x_{it} values satisfy the maintenance completion constraints. If the maintenance completion constraints are satisfied, proceed to step 4, otherwise proceed to step 2.

4. Check whether the generated MSP i.e., the z_{ik} and the corresponding x_{it} values satisfy the crew and the precedence constraints. If the crew and the precedence constraints are satisfied, proceed to step 7, otherwise go to step 5.

5. Check which of the crew or precedence constraints are violated.

6. If a precedence or crew constraint involving a pair of generators $i1$ and $i2$ is violated, randomly generate the maintenance start period $z_{i2,k}$ of the second unit from its maintenance window, keeping the MSP $z_{i1,k}$ of the first unit $i2$ fixed at its former value. Go to step 4.

7. Check whether the resource and the reserve constraints are satisfied. If the any of the constraints are violated, go back to step 2.

8. If the constraints (maintenance completion, precedence, crew, resource & reserve) are satisfied, then a candidate solution (a set of z_{ik}'s) is obtained.

9. Check whether the z_{ik} values comprising the candidate solution (maintenance schedule) are present in the respective tabu lists. That is, check whether the

candidate solution is *tabu.*

10. If the z_{ik} values are not present, i.e., the solution is not tabu, store the values of z_{ik} in the respective tabu lists using the first in-first out (FIFO) mechanism. Compute and store the objective function value for the candidate solution. The candidate solution is now the current solution. Update the iteration counter and go to step 14. Otherwise go to step 11.

    Note: A candidate solution which is not tabu is always accepted into the tabu lists. However it's objective function value will not be retained as the current best if it is not better than the current best solution obtained thus far. This strategy ensures that poor solutions are accepted into the tabu lists. This may lead the tabu search process to investigate better solutions in the latter iterations.

11. If the z_{ik} values comprising the candidate solution are already present in the tabu lists, then the solution represented by the set of z_{ik}'s is *tabu.*

12. When a candidate solution is found to be *tabu,* check if it passes the aspiration criterion test. Compute the objective function value for the tabu solution. If the resulting objective function value is better than the best obtained thus far, then override the tabu status of the solution. Accept the candidate solution and store it in the tabu lists. The candidate solution now becomes the current solution. Update the iteration counter and go to step 14.

13. If the tabu candidate solution does not pass the aspiration criterion test, then discard it. Go to step 16.

14. Form a new candidate list using the current solution. i.e., generate neighbour solutions for the solution just accepted into the tabu lists. Go to step 15.

15. Pick the best candidate member in the candidate list for admission into the tabu list. Go to step 9.

16. Pick the next best member in the candidate list. Go to step 9.

17. Check for the stopping criteria. If they are satisfied, terminate the tabu search process. Otherwise go back to step 15.

4.2.3 Random generation of the maintenance starting periods

The maintenance starting periods are randomly generated as follows:

Generate a random number r from a uniform distribution 0 to 1 $\{r \sim u(0,1)\}$. The maintenance start period (MSP) for a generator i with the maintenance window given by $[E_i, L_i]$ is randomly computed as:

$$\mathrm{MS}P = \mathrm{Int}\,\{E_i + r(L_i - E_i)\} \tag{4.1}$$

4.2.4 Forming a candidate list

When a candidate solution is accepted into the tabu lists, it becomes the current solution. This current solution is used to generate a solution neighborhood i.e, a candidate list. The members of this list are then considered for admission into the tabu lists in the next iterations.

A candidate list of members is generated from a current solution by assigning new maintenance start periods (MSP) to a single unit. These maintenance start periods are chosen from the maintenance window of the unit in question. For example, let the current solution (maintenance schedule) for the 4-unit system illustrated in chapter 3 be [1 5 7 1]. That is, unit 1 *begins* maintenance in week 1, the second unit in week 5 and so on. To generate a candidate list for this current solution, a single unit, say unit 4 is chosen and its MSP is changed to values which lie within it maintenance window [1, 8]. The number of candidates generated depend on the size of the maintenance window of the unit. [1 5 7 2], [1 5 7 3], [1 5 7 4], [1 5 7 5], etc are members comprising the candidate list. The best among these is chosen for admission into the tabu lists in the next iteration.

Chapter 5

Zero-One Additive Algorithm

In this chapter, the exact solution of the maintenance scheduling problem using the zero-one additive algorithm is presented.

5.1 Introduction

The Additive algorithm is used for obtaining the optimal solution of a zero-one integer program. The algorithm is actually a variation of the more general Branch & Bound method. It is sometimes referred to as the *0-1 implicit enumeration algorithm*, since only a small portion of the total 2^n solutions are investigated explicitly during the solution process [30].

Let the given problem be of the minimization type and define it as

$$\text{minimize} \quad z = \sum_{j=1}^{n} c_j x_j \tag{5.1}$$

subject to

$$\sum_{j=1}^{n} a_{ij}x_j + S_i = b_i, \quad i = 1, 2, \cdots, m \tag{5.2}$$

$$x_j = 0 \text{ or } 1, \quad j =, 2, \cdots, n$$

$$S_i \geq 0, \quad i = 1, 2, \cdots, m$$

where S_i is the slack variable associated with the ith constraint. For the purpose of the 0-1 additive algorithm, all the constraints must be of the type ($\leq$). Moreover, every c_j should be ≥ 0.

The 0-1 additive algorithm tries to enumerate all 2^n possible solutions of the problem. However, it recognizes that some solutions can be discarded automatically without being investigated implicitly. Hence, in the final analysis, only a portion of the 2^n solutions needs be investigated explicitly. This idea is implemented as follows: Initially, all the variables are assumed to be at zero level. Since the corresponding solution is not feasible(i.e., some slack variables S_i may be negative), it will be necessary to elevate some variables to level one. The procedure calls for elevating one (or perhaps more) variable at a time, provided there is evidence that this step will be moving the solution toward feasibility, that is, making $S_i \geq 0$ for all i. To ensure the proper selection of the variables to be elevated to level one, tests have been developed and these are presented in section 5.3

5.2 Definitions

The following definitions are introduced to explain the zero-one algorithm [30].

1. *Free variable*: At any node of the zero-one branch & bound tree, a binary variable is called free, if it is not fixed by any of the branches leading to this node. A free variable is initially at zero level but may be elevated to level one if this can improve the infeasibility of the problem.

2. *Partial solution*: A partial solution provides a specific binary assignment for some of the variables in the sense that it fixes the values of one or more variables at zero or one. The partial solution can be expressed as an *ordered set*. Let J_t represent the partial solution at the tth node (or iteration), and let the notation $+j$ $(-j)$ represent $x_j = 1$ $(x_j = 0)$. Thus the elements of J_t consist of the subscripts of the fixed variables with the plus(minus) sign signifying that the variable is one(zero). The set J_t must be ordered in the sense that each new element is always augmented *on the right* of the partial solution. The partial solutions can be used to define the nodes in the branch-and-bound tree since the branches leading to a node actually represent a partial binary assignment to some variables.

3. *Fathoming of partial solutions*: A partial solution is said to be fathomed if:

   - It cannot lead to a better value of the objective function.

- It cannot lead to a feasible solution.

A fathomed partial solution means that it is not promising to further branch its associated node, since all the solutions that could be generated from the node are either inferior or infeasible.

Partial solutions can be generated successively from one another. The general rule for generating the next partial solution from a *fathomed* one is as follows: If *all* the elements of a *fathomed* partial solution are negative, the enumeration is complete. Otherwise select the rightmost *positive* element, complement it, and *then delete all the (negative) elements to its right.* The process of complementing the *rightmost positive* element is sometimes called *backtracking.*

5.3 The Zero-One algorithm

The general version of the additive algorithm is now presented by using the concept of partial solution. The exclusion tests used to fathom partial solution and augment new variables at level one are also generalized for the zero-one problem [30].

Consider the general minimization problem defined by equations 5.1 and 5.2. Let J_t be the partial solution at node t (initially, $J_o = \emptyset$, which means that all variables are free) and assume z^t is the associated value of the objective function z while $\bar{z}$ is the current best upper bound (initially $\bar{z} = \infty$).

Test 1

For any free variable x_r, if $a_{ir} \geq 0$ for all i corresponding to $S_i^t < 0$, then x_r cannot improve the infeasibility of the problem and must be discarded as nonpromising.

Test 2

For any free variable x_r, if

$$c_r + z^t \geq \bar{z} \tag{5.3}$$

then x_r cannot lead to an improved solution and hence must be discarded.

Test 3

Consider the ith constraint

$$a_{i1}x_1 + a_{i2}x_2 + ... + a_{in}x_n + S_i = b_i \tag{5.4}$$

for which $S_i^t < 0$. Let N_t define the set of free variables not discarded by tests 1 and 2. None of the free variables in N_t are promising if for at least one $S_i^t < 0$, the following condition is satisfied:

$$\sum_{j \in N_t} \min \quad \{o, a_{ij}\} > S_i^t \tag{5.5}$$

This actually implies that the set N_t cannot lead to a feasible solution and hence must be discarded altogether. In this case J_t is said to be fathomed.

Test 4

If $N_t \neq \emptyset$, the branching variable x_k is selected as the one corresponding to

$$v_k^t = \max \ (v_j^t) \quad j \in N_t \tag{5.6}$$

where

$$v_j^t = \sum_{i=1}^{m} \min \quad (0, S_i^t - a_{ij}) \tag{5.7}$$

If $v_k^t = 0$, $x_k = 1$ together with J_t yields an improved feasible solution. In this case, J_{t+1} which is defined by J_t with $\{k\}$ augmented on the right, is fathomed. Otherwise, the foregoing test are applied again to J_{t+1} until the enumeration is completed, that is, until *all* the elements of the *fathomed* partial solution are negative.

5.4 Implementation details

The flow chart of the 0-1 implicit enumeration algorithm used to solve the maintenance scheduling problem is presented in Fig. 5.1.

The MS problem has a number of equality constraints. These are required to ensure that a generator is scheduled for maintenance just once during the planning horizon. The zero-one algorithm requires all the constraints to be of the type ($\leq$). Therefore each equality constraint in the problem was transformed into a pair of $\leq$ and $\geq$ constraints. The $\geq$ constraint was then converted into a $\leq$ constraint by multiplying the constraint throughout by the negative sign. Similarly other $\geq$ constraints were converted into $\leq$ constraints.

The size of the MS problem depends on the number of generators in a power system, their maintenance window limits and on the number of periods in the planning

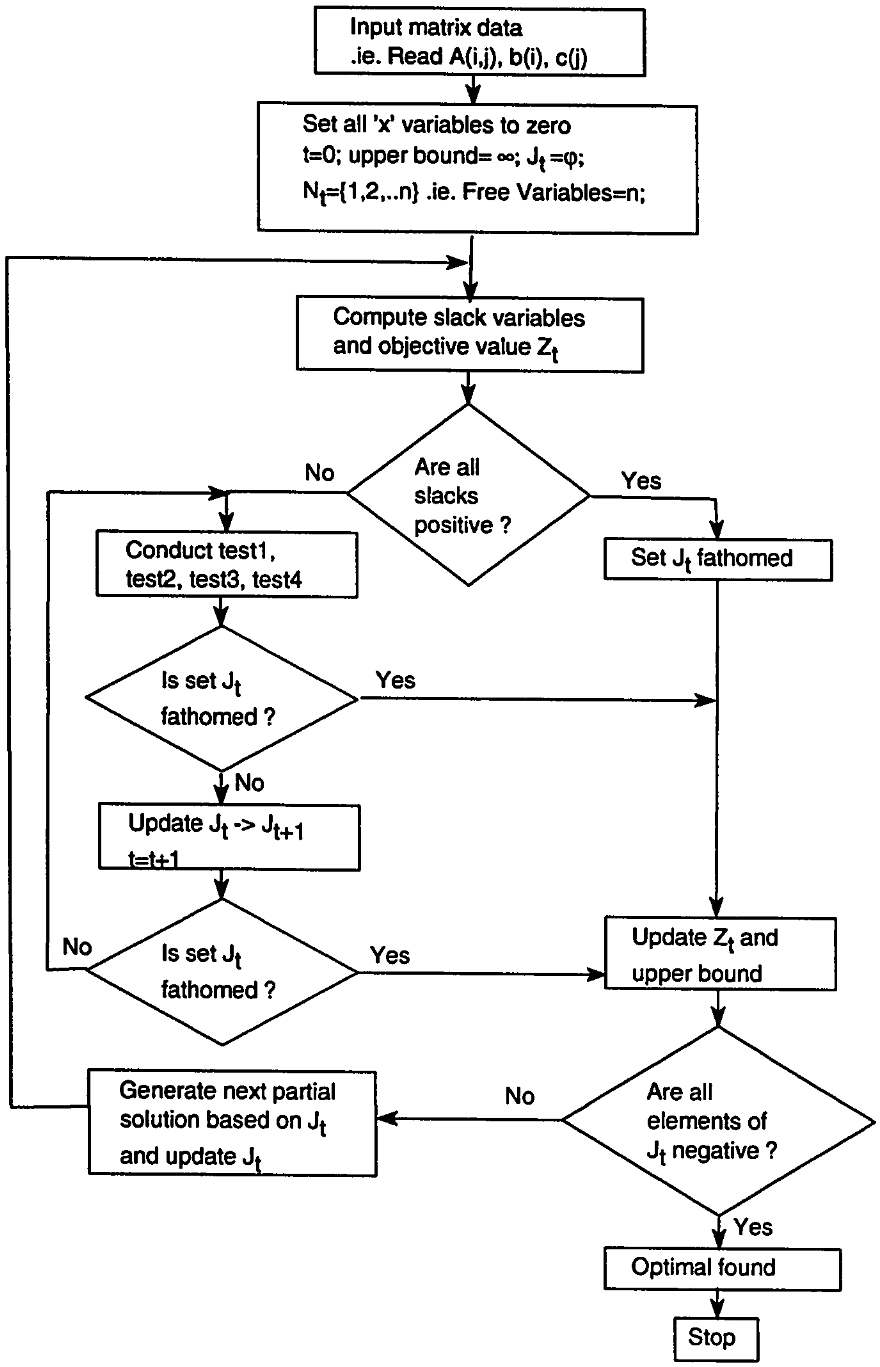

Figure 5.1: Flow chart of the zero-one additive algorithm.

horizon. These three factors combine to generate a huge number of maintenance schedules with only a very few of them satisfying all constraints. The 0-1 algorithm is based on exhaustive implicit or explicit search. Using such exhaustive search-based techniques to schedule large number of generators for maintenance may result in excessive computation. Therefore heuristic techniques capable of providing near-optimal solutions in low execution times are worth developing.

Chapter 6

Simulation Results

In this chapter, the simulation results obtained using the zero-one integer program and the proposed tabu search method are presented. The tabu search and zero-one integer programs were written in the programming language *turbobasic* and run on an *intel-486 PC.*

6.1 4-Unit system

The system consists of four generators rated 200, 200, 300 and 90 MW each. Maintenance schedules for these generators are obtained using the tabu search and zero-one implicit enumeration techniques. The length of the maintenance planning horizon is taken to be 8 weeks. The data of the 4-unit system is given in Table 6.1 [16]. The weekly peak loads and the gross reserves for the time horizon considered are given in Table 6.2.

For the 4-unit system, the maintenance schedules were obtained subject to the following constraints.

1. *Maintenance completion*

   Each unit has to be committed for maintenance just once during the maintenance planning horizon of 8 weeks. When a unit commences maintenance, it should remain in the maintenance state for a period equal to it's maintenance duration without any interruption. Also it has to complete maintenance before the end of the planning horizon.

2. *Crew constraint*

   A single crew constraint involving units 1 and 2 was considered. These two units have a single maintenance crew assigned for their upkeep. As a result the crew cannot carry out maintenance work on units 1 and 2 simultaneously.

3. *Precedence constraint*

   A single precedence constraint involving units 1 and 2 was considered. The precedence requirement was that unit 1 has to be maintained *first* during the planning horizon. Unit 2 can commence maintenance only after unit 1 has finished maintenance.

Table 6.1: 4-Unit system data

i	R_i	E_i	L_i	M_i	a	b	c	v_i
1	200	1	5	4	78	7.97	0.00482	0.2
2	200	1	7	2	80	7.80	0.00462	0.2
3	300	1	7	2	110	7.65	0.00465	0.4
4	90	1	8	1	60	8.40	0.00610	0.5

Table 6.2: Weekly peak loads and gross reserves for the 4-Unit system

$t(week)$	Demand $D_t(MW)$	Gross reserve $G_t(MW)$
1	249	541
2	265	525
3	276	514
4	279	511
5	256	534
6	307	483
7	187	603
8	295	495

4. *Resource constraint*

   The maintenance outage capacity (sum total of the capacity out on maintenance) should not exceed the gross reserve during any week in the planning horizon.

5. *Reserve constraint*

   The total available power from units not in maintenance must be greater than the demand plus the reserve. For the 4-unit system, a minimum reserve equal to 20% of the maximum weekly peak was kept.

The objective criteria considered were: Levelling the reserve and minimization of the total generator operating cost.

6.1.1 Levelling the reserve: Tabu search

The maintenance schedule of the 4-unit system for the objective criterion 'levelling the reserve' is shown in Fig. 6.1. It can be seen that unit 1 begins maintenance in the first week and is in the maintenance state for 4 consecutive weeks. Unit 2 commences maintenance in the fifth week and remains in the state for a period equal to its maintenance duration of 2 weeks. It can be observed that unit 2 begins maintenance only after unit 1 has finished maintenance thereby satisfying the precedence constraint. Also units 1 and 2 are not in maintenance simultaneously. Thus the

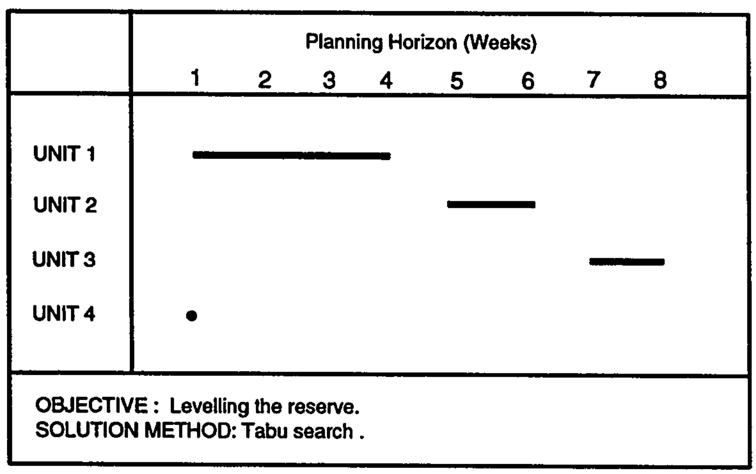

Figure 6.1: 4-unit maintenance schedule (levelling the reserve) by tabu search

Table 6.3: 4-Unit system output summary: Levelling the reserve by Tabu search

Week	*Units in maintenance*	*Capacity on maintenance*	*Available generation*	*Peak load*
1	4,1	290	500	249
2	4	200	590	265
3	4	200	590	276
4	4	200	590	279
5	2	200	590	256
6	2	200	590	307
7	3	300	490	187
8	3	300	490	295

crew constraint is satisfied. Units 3 and 4 are scheduled for maintenance in the seventh and first week respectively. All the units complete their maintenance without any interruption thus satisfying the maintenance completion constraint. The units are also maintained just once during the planning horizon. It took about 5 seconds for the tabu search program to obtain the maintenance schedule. A summary of the schedule is shown in Table 6.3.

6.1.2 Levelling the reserve: 0-1 implicit enumeration

The maintenance schedule of the 4-unit system obtained using the zero-one integer program is shown in Fig. 6.2. A summary of the schedule is shown in Table 6.4. It took about 57 minutes for the program to complete execution. It can be observed that the maintenance schedule obtained by the 0-1 implicit enumeration algorithm is exactly similar to the one obtained using the tabu search. The implicit enumeration algorithm gives the exact optimal solution [30]. Thus the proposed tabu search method also gives an optimal solution to the 4-Unit maintenance scheduling problem and it does so at very low execution times. It took only 5 seconds for the tabu search method to complete execution whereas the zero-one program took about 57 minutes. The implementation of the zero-one program resulted in a large constraint matrix (A) with dimensions 98×59. A total of 59 binary variables were required to model the 4-unit maintenance scheduling problem.

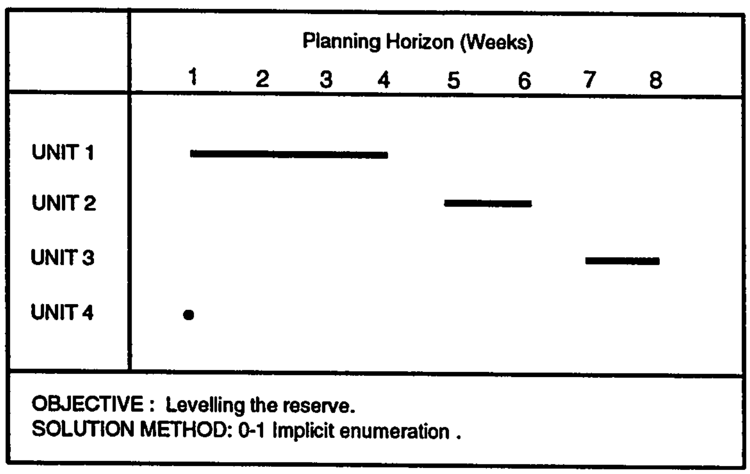

Figure 6.2: 4-unit maintenance schedule(levelling the reserve) by 0-1 implicit enumeration

Table 6.4: 4-Unit system output summary: Levelling the reserve by 0-1 program

Week	*Units in maintenance*	*Capacity on maintenance*	*Available generation*	*Peak load*
1	4,1	290	500	249
2	4	200	590	265
3	4	200	590	276
4	4	200	590	279
5	2	200	590	256
6	2	200	590	307
7	3	300	490	187
8	3	300	490	295

and processing time. It is therefore preferable to use the proposed technique of tabu search for the purpose of scheduling the generating units for maintenance.

6.1.3 Minimizing the total generator operating costs: Tabu search

The maintenance schedule of the 4-unit system for the objective criterion 'Minimizing the total generator operating costs' is shown in Fig. 6.3. The schedule is summarized in Table 6.5. It can be seen that unit 1 begins maintenance in the first week and is in the maintenance state for 4 consecutive weeks. Unit 2 commences maintenance in the fifth week and remains in the state for a period equal to its maintenance duration of 2 weeks. It can be observed that unit 2 begins maintenance only after unit 1 has finished maintenance thereby satisfying the precedence constraint. Also units 1 and 2 are not in maintenance simultaneously. Thus the crew constraint is satisfied. Units 3 commences maintenance in the seventh week and unit 4 begins maintenance in the seventh week. All the units complete their maintenance without any interruption thus satisfying the maintenance completion constraint. The units are also maintained just once during the planning horizon. It took about 54 seconds for the tabu search program to obtain the maintenance schedule.

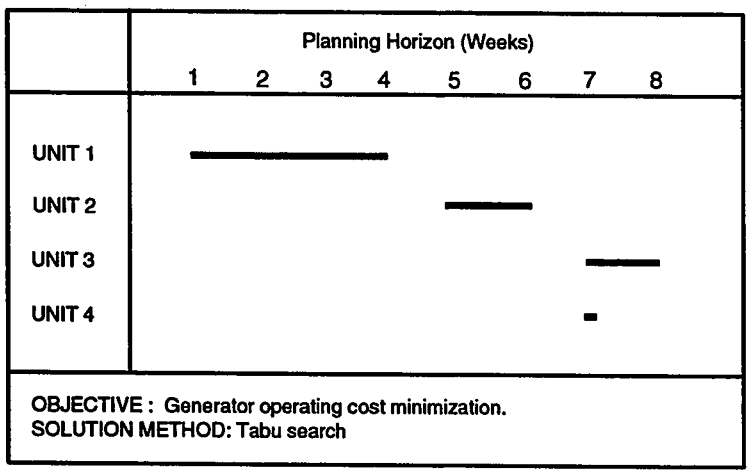

Figure 6.3: 4-unit maintenance schedule(Minimizing total generator operating cost) by Tabu search

Table 6.5: 4-Unit system output summary: Minimizing total generator operating costs by tabu search

Week	*Units in maintenance*	*Capacity on maintenance*	*Available generation*	*Peak load*
1	4,1	200	590	249
2	4	200	590	265
3	4	200	590	276
4	4	200	590	279
5	2	200	590	256
6	2	200	590	307
7	3	390	400	187
8	3	300	490	295

6.1.4 Minimizing the total generator operating costs: 0-1 implicit enumeration

The maintenance schedule obtained by the 0-1 implicit enumeration method is shown in Fig. 6.4. The maintenance schedule is exactly similar to the one obtained using tabu search. Therefore the proposed tabu search method gives an optimal solution for the 4-unit system for the objective 'Minimizing the total generator operating costs'. It took about 105 minutes for the 0-1 program to finish execution.

6.2 5-Unit system

The system consists of five generators rated 150, 150, 130, 90 and 50 MW each. The length of the maintenance planning horizon considered is 8 weeks. The data of the 5-unit system is given in Table 6.7 [20]. The weekly peak loads and the gross reserves for the time horizon considered are given in Table 6.8.

It is required to schedule each of the 5 units for maintenance just once during the planning horizon of 12 weeks. The constraints that were considered are given below:

1. Maintenance completion constraints.

2. Crew constraint.

3. Precedence constraints.

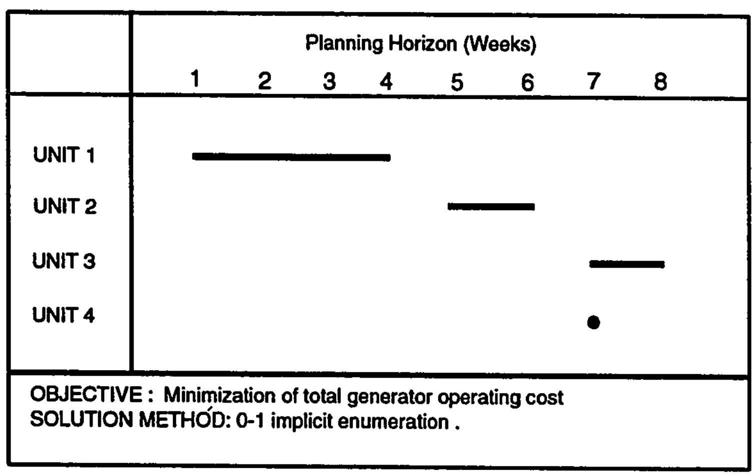

Figure 6.4: 4-unit maintenance schedule(Minimizing total generator operating cost) by 0-1 implicit enumeration

Table 6.6: 4-Unit system output summary: Minimizing total generator operating costs by 0-1 program

Week	*Units in maintenance*	*Capacity on maintenance*	*Available generation*	*Peak load*
1	4, 1	200	590	249
2	4	200	590	265
3	4	200	590	276
4	4	200	590	279
5	2	200	590	256
6	2	200	590	307
7	3	390	400	187
8	3	300	490	295

Table 6.7: 5-Unit system data

i	R_i	E_i	L_i	M_i
1	150	1	5	2
2	150	6	10	2
3	130	8	11	2
4	90	8	11	2
4	50	8	11	2

Table 6.8: Weekly peak loads and gross reserves for the 5-Unit system

$t(week)$	Demand $D_t(MW)$	Gross reserve $G_t(MW)$
1	215	355
2	228	342
3	215	355
4	228	342
5	219	351
6	224	346
7	216	354
8	221	349
9	228	342
10	215	355
11	215	355
12	219	351

4. Resource constraints.

5. Reserve constraints.

The precedence constraint specifies that unit 2 should be maintained before unit 3. The crew constraint specifies that units 4 and 5 cannot be simultaneously on maintenance during any stage during the planning horizon. The reserve constraints ensure that a minimum reserve equal to about 20 % of the peak demand is maintained throughout the planning horizon.

6.2.1 Levelling the reserve: Tabu search

The 5-unit maintenance schedule obtained by tabu search is depicted in Fig. 6.5. The summary of the program output is shown in Table 6.9. The schedule satisfies all the constraints that were considered. Units 4 and 5 are not on maintenance at the same time. The crew constraint is thus satisfied. It can also be observed that unit 2 is being maintained before unit 3, thereby satisfying the precedence constraint. It took about 9 seconds for the tabu search to obtain the schedule.

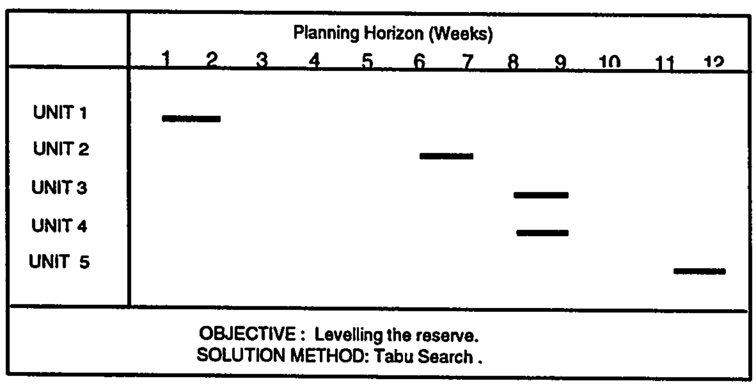

Figure 6.5: 5-unit maintenance schedule (levelling the reserve) by Tabu search

Table 6.9: 5-Unit system output summary: Levelling the reserve by tabu search

Week	*Units in maintenance*	*Capacity on maintenance*	*Available generation*	*Peak load*
1	4	800	4500	3800
2	4	800	4500	3700
3	1, 7	1300	4000	3300
4	1, 8	1200	4100	3300
5	3	800	4500	3800
6	9	100	5200	4300
7	10	100	5200	4300
8	-	-	5300	4400
9	6	500	4800	4100
10	2	1000	4300	3600
11	2	1000	4300	3600
12	5	500	4800	4000

6.2.2 Levelling the reserve: 0-1 implicit enumeration

The 5-unit maintenance schedule obtained by the 0-1 program is depicted in Fig. 6.6. The summary of the program output is shown in Table 6.10. The schedule satisfies all the constraints that were considered. Units 4 and 5 are not on maintenance at the same time. The crew constraint is thus satisfied. It can also be observed that unit 2 is being maintained before unit 3, thereby satisfying the precedence constraint. It took about 71 minutes for the 0-1 program to obtain the schedule.

From figures 6.5 and 6.6, it can be observed that the schedule obtained by tabu search is similar to the one obtained by the 0-1 program. Therefore for the 5-unit system considered, the solution obtained by the tabu search is optimal.

6.3 10-Unit system

The 10-Unit system is comprised of the generating units shown in Table 6.11 [31]. The monthly peak loads are shown in Table 6.12. It is required to schedule each of these units for maintenance once during a planning horizon of 8 months. A scheduling period is considered to be a month in this example. The constraints considered are the maintenance completion, crew, precedence and resource constraints. The crew constraint involves units 9 and 10. The precedence constraint specifies that unit 1 should be maintained before unit 2.

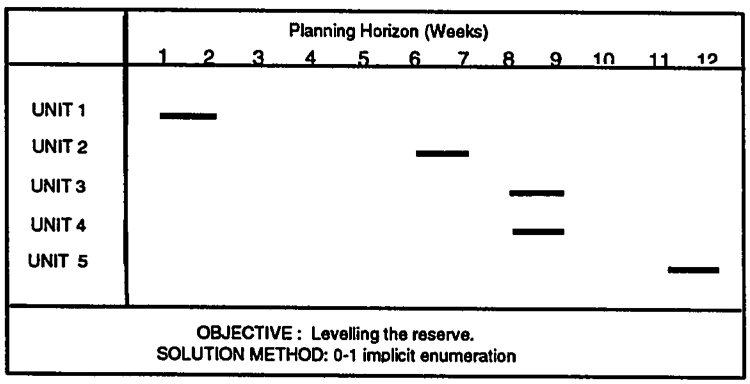

Figure 6.6: 5-unit maintenance schedule(levelling the reserve) by 0-1 implicit enumeration

Table 6.10: 5-Unit system output summary: Levelling the reserve by 0-1 program

Week	*Units in maintenance*	*Capacity on maintenance*	*Available generation*	*Peak load*
1	4	800	4500	3800
2	4	800	4500	3700
3	1, 7	1300	4000	3300
4	1, 8	1200	4100	3300
5	3	800	4500	3800
6	9	100	5200	4300
7	10	100	5200	4300
8	-	-	5300	4400
9	6	500	4800	4100
10	2	1000	4300	3600
11	2	1000	4300	3600
12	5	500	4800	4000

Table 6.11: 10-Unit system data

i	R_i	Earliest starting month E_i	Latest starting month L_i	Maintenance duration M_i
1	1000	1	5	2
2	1000	1	7	2
3	800	1	8	1
4	800	1	7	2
5	500	1	8	1
6	500	1	8	1
7	300	1	5	1
8	200	1	5	1
9	100	1	4	1
10	100	1	4	1

Table 6.12: Monthly peak loads and gross reserves for the 10-Unit system

$t(month)$	Demand $D_t(MW)$	Gross reserve $G_t(MW)$
1	3800	1500
2	3700	1600
3	3300	2000
4	3300	2000
5	3800	1500
6	4300	1000
7	4300	1000
8	4400	900

6.3.1 Levelling the reserve: Tabu search

The maintenance schedule of the 10-unit system for the objective criterion 'levelling the reserve' is shown in Fig. 6.7. It can be observed that the various units complete their maintenance without interruption and they do so in a time period which is exactly equal to their maintenance durations. Thus the maintenance completion constraint is satisfied. It can be seen that units 9 and 10 are not maintained simultaneously. Thus the crew constraint is satisfied. The precedence constraint is also satisfied with unit 1 being maintained before unit 2. A summary of the schedule is given in Table 6.13. It took about 12 seconds for the tabu search to find the maintenance schedule.

6.3.2 Levelling the reserve: 0-1 implicit enumeration

A total of 141 binary variables were required to model the 10-unit maintenance scheduling problem. Out of these, 61 z_{it} variables were required to represent all the possible maintenance starting periods of the units and 80 x_{it} variables were needed to represent the states of the units in each of the various scheduling periods. The implementation of the zero-one program resulted in the constraint matrix whose dimensions were 168 $\times$ 141. A summary of the maintenance schedule is given in Table 6.14. The maintenance schedule obtained is shown in Fig. 6.8. It took about 245 minutes for the program to complete execution.

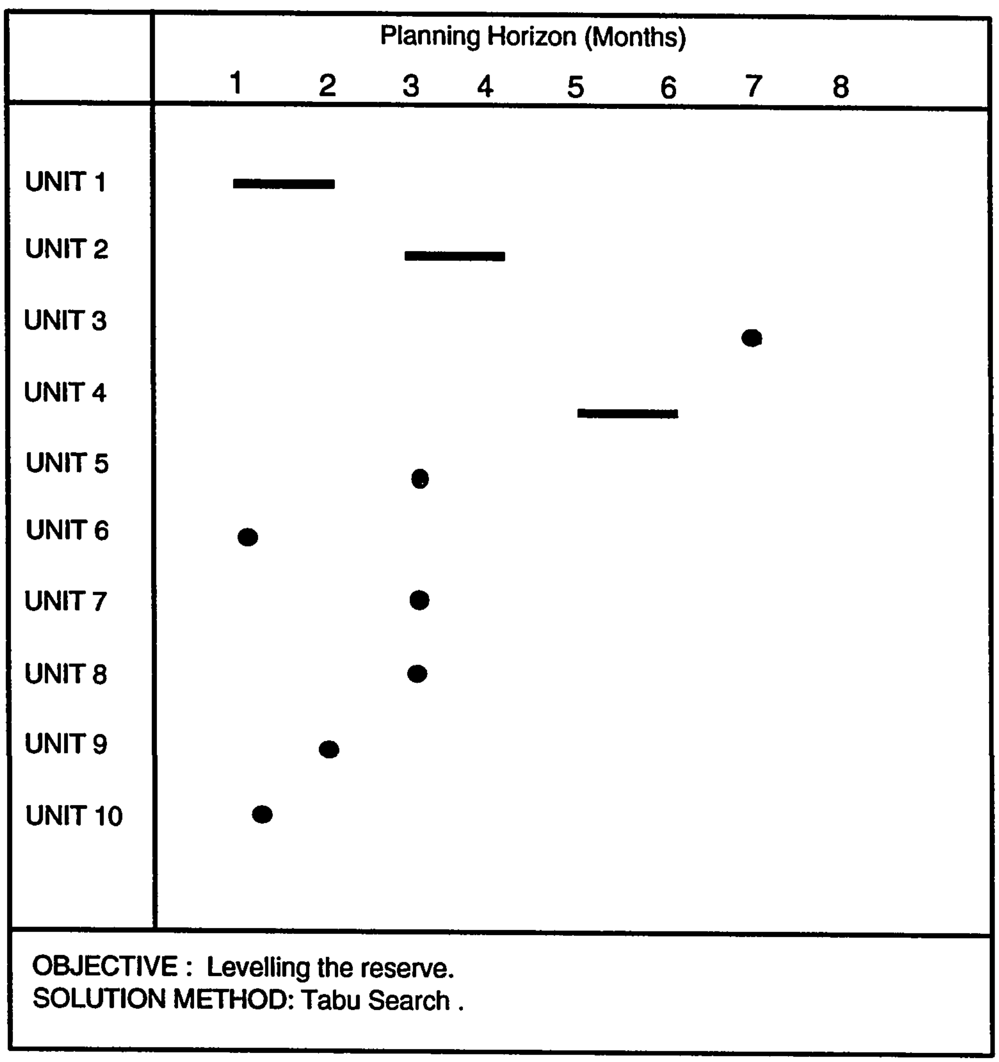

Figure 6.7: 10-unit maintenance schedule by Tabu search: Levelling the reserve

Table 6.13: 10-Unit system output summary: Levelling the reserve by tabu search

Month	*Units in maintenance*	*Capacity on maintenance*	*Available generation*	*Peak load*
1	1, 6, 10	1600	3700	3800
2	1, 9	1100	4200	3700
3	2, 5, 7, 8	2000	3300	3300
4	2	1000	4300	3300
5	4	800	4500	3800
6	4	800	4500	4300
7	3	800	4500	4300
8	-	-	5300	4400

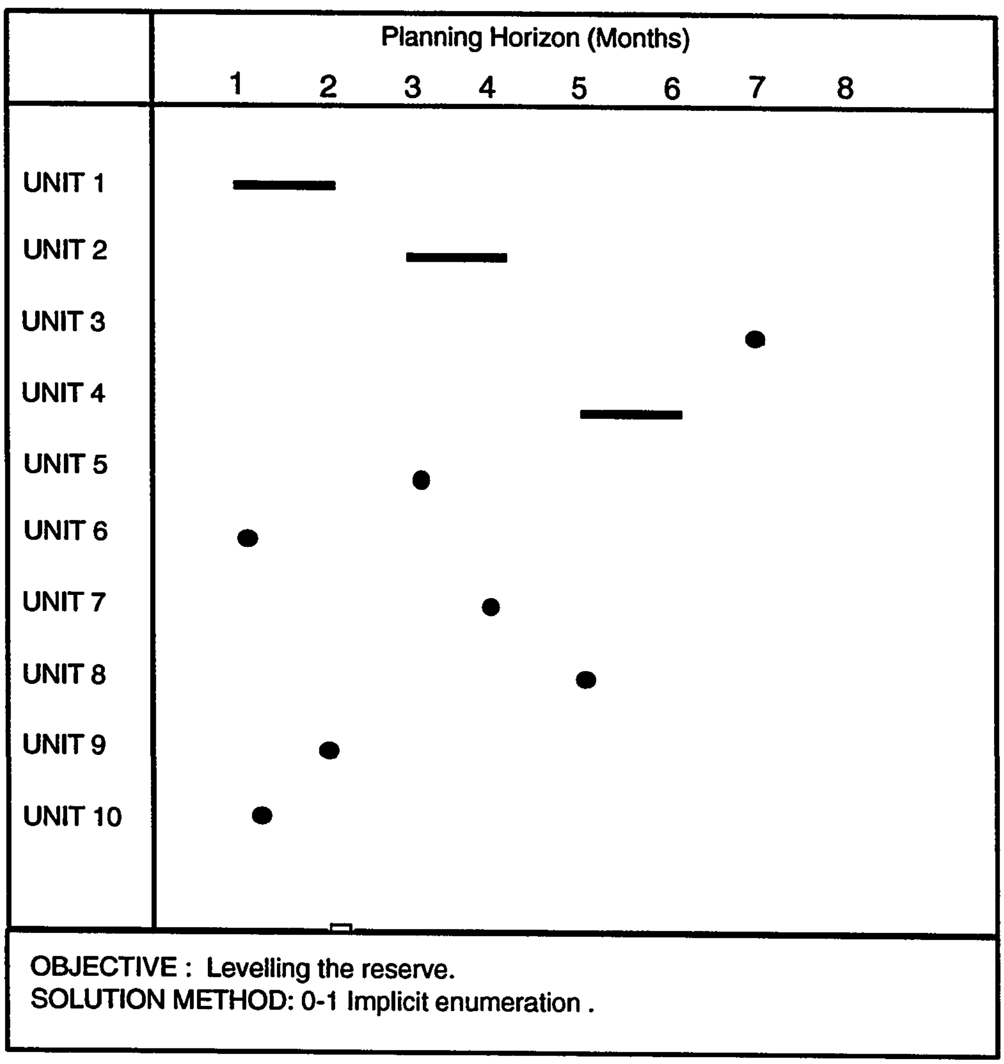

Figure 6.8: 10-unit maintenance schedule by 0-1 program: Levelling the reserve

Table 6.14: 10-Unit system output summary: Levelling the reserve by 0-1 program

Month	*Units in maintenance*	*Capacity on maintenance*	*Available generation*	*Peak load*
1	1, 6, 10	1600	3700	3800
2	1, 9	1100	4200	3700
3	2, 5	1500	3800	3300
4	2, 7	1300	4000	3300
5	4, 8	1000	4300	3800
6	4	800	4500	4300
7	3	800	4500	4300
8	-	-	5300	4400

6.4 22-unit system

The 22-unit system is a real-life size problem. The length of the planning horizon considered is 52 weeks. It is required to schedule each of the 22 generators for maintenance just once during the planning horizon subject to the following constraints.

1. Maintenance completion constraints.

2. Crew constraints.

3. Precedence constraints.

4. Resource constraints.

5. Reserve constraints.

A total of two crew constraints were considered. The first crew constraint involved units 15 & 16. The units involved in the second crew constraint are 21 & 22.

The 22-unit system is also subject to two precedence constraints. The first precedence constraint involves units 2 & 3 and the units involved in the second precedence constraints are 5 & 6.

The data of the 22 unit system is presented in Tables 6.15, 6.4 and 6.17 respectively [16].

Table 6.15: 22-Unit system data

i	R_i	E_i	L_i	M_i	a	b	c	v_i
1	100	1	47	6	70	8.00	0.00585	0.25
2	100	1	50	3	70	8.00	0.00580	0.20
3	100	1	50	3	70	8.00	0.00580	0.20
4	100	1	50	3	70	8.00	0.00580	0.20
5	90	1	47	6	60	8.00	0.00610	0.35
6	90	1	49	4	60	8.00	0.00610	0.30
7	95	1	50	3	68	8.00	0.00579	0.20
8	100	1	49	4	72	8.00	0.00565	0.20
9	650	27	48	5	525	7.00	0.00120	0.52
10	610	6	11	12	510	7.20	0.00142	0.50
11	91	1	49	4	62	8.25	0.00600	0.20
12	100	1	45	8	74	8.15	0.00578	0.30
13	100	1	50	3	70	8.00	0.00580	0.20
14	100	1	47	6	70	8.00	0.00585	0.25
15	220	1	48	5	85	7.90	0.00460	0.25
16	220	1	47	6	87	7.95	0.00464	0.25
17	100	1	48	5	69	8.18	0.00570	0.20
18	100	1	48	5	69	8.17	0.00572	0.25
19	220	1	50	3	81	7.90	0.00463	0.25
20	220	1	50	3	82	7.95	0.00462	0.25
21	240	1	50	3	82	7.40	0.00410	0.30
22	240	1	48	5	80	7.42	0.00415	0.30

Table 6.16: Weekly peak loads and gross reserves for the 22-Unit system (continued)

t	Demand D_t	Gross reserve G_t
1	1694	2292
2	1714	2272
3	1844	2142
4	1694	2292
5	1684	2302
6	1763	2223
7	1663	2323
8	1583	2403
9	1543	2443
10	1586	2400
11	1690	2296
12	1496	2490
13	1456	2530
14	1396	2590
15	1443	2543
16	1273	2713
17	1263	2723
18	1655	2331
19	1695	2291
20	1675	2311
21	1805	2181
22	1705	2281
23	1766	2220
24	1946	2040
25	2116	1870
26	1916	2070

Table 6.17: Weekly peak loads and gross reserves for the 22-Unit system

t	Demand D_t	Gross reserve G_t
27	1737	2249
28	1927	2059
29	2137	1849
30	1927	2059
31	1907	2079
32	1888	2098
33	1818	2168
34	1848	2138
35	2118	1868
36	1879	2107
37	2089	1897
38	1989	1997
39	1999	1987
40	1982	2004
41	1672	2314
42	1782	2204
43	1772	2214
44	1556	2430
45	1706	2280
46	1806	2180
47	1826	2160
48	1906	2080
49	1999	1987
50	2109	1877
51	2209	1777
52	1779	2207

6.4.1 Levelling the reserve : Tabu search

The 22-unit maintenance schedule for the objective criterion 'Levelling the reserve' is shown in Fig. 6.9. All the constraints that were considered are satisfied. Units 15 and 16 are not simultaneously in maintenance. Similar is the case with units 21 and 22. Therefore crew constraints are satisfied. The precedence constraints are also satisfied with unit 2 maintained before unit 3 and unit 5 maintained before unit 6. It took about 40 seconds for the tabu search program to complete execution. Tables 6.18, 6.19 and 6.20 show a summary of the maintenance schedule obtained by the tabu search.

6.4.2 Minimizing total generator operating cost : Tabu search

The 22-unit maintenance schedule for the objective criterion 'minimizing total generator operating cost' is shown in Fig. 6.10. Tables 6.21, 6.22 and 6.23 show a summary of the maintenance schedule. All the constraints that were considered in the problem are satisfied. It took about 166 minutes for the tabu search program to complete execution.

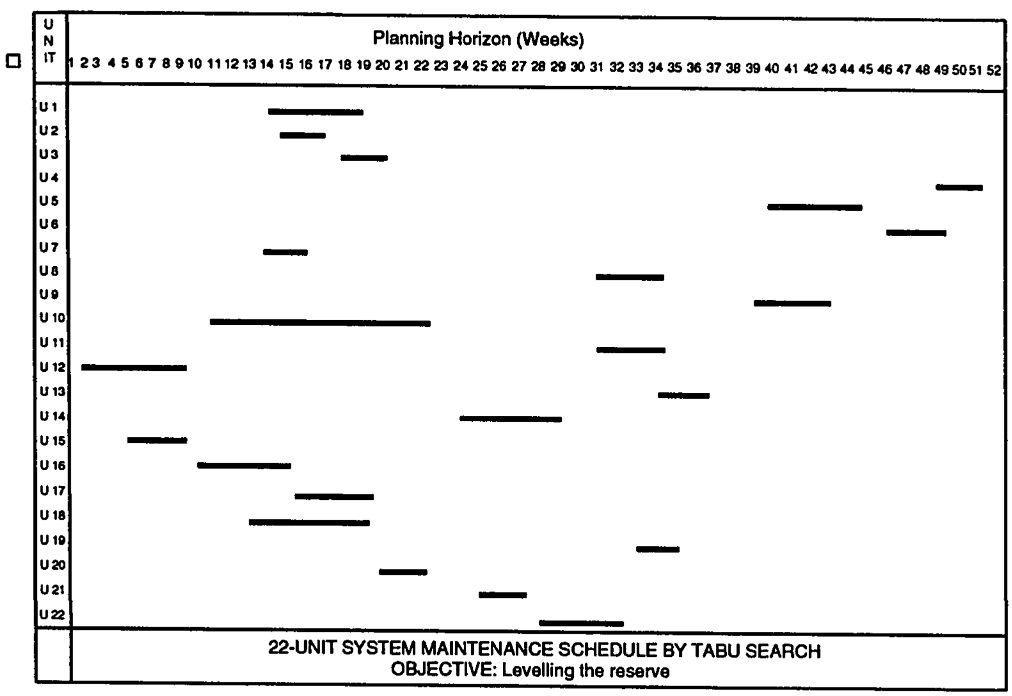

Figure 6.9: 22-unit maintenance schedule by Tabu search: Levelling the reserve

Table 6.18: 22-Unit system maintenance schedule (levelling the reserve)by tabu search

Unit	M_i	*MSP*	*Weeks in maintenance*
1	6	14	14, 15, 16, 17, 18, 19
2	3	15	15, 16, 17
3	3	18	18, 19, 20
4	3	49	49, 50, 51
5	6	40	41, 42, 43, 44, 45
6	4	46	46, 47, 48, 49
7	3	14	14, 15, 16
8	4	31	31, 32, 33, 34
9	5	39	39, 40, 41, 42, 43
10	12	11	11, 12, 13, 14, 15, 16, 17, 18, 19, 20, 21
11	4	31	31, 32, 33, 34
12	8	2	2, 3, 4, 5, 6, 7, 8, 9
13	3	34	34, 35, 36
14	6	24	24, 25, 26, 27, 28, 29
15	5	5	5, 6, 7, 8, 9
16	6	10	10, 11, 12, 13, 14, 15
17	5	15	15, 16, 17, 18, 19
18	5	13	13, 14, 15, 16, 17
19	3	33	33, 34, 35
20	3	20	20, 21, 22
21	3	25	25, 26, 27
22	5	28	28, 29, 30, 31, 32

Table 6.19: 22-Unit system output summary: Levelling the reserve

Week	*Units in maintenance*	*Capacity on maintenance*	*Available generation*	*Peak load*
1	-	-	3986	1694
2	12	100	3886	1714
3	12	100	3886	1844
4	12	100	3886	1694
5	12, 15	320	3666	1684
6	12, 15	320	3666	1763
7	12, 15	320	3666	1663
8	12, 15	320	3666	1583
9	12, 15	320	3666	1543
10	16	220	3766	1586
11	10, 16	830	3156	1690
12	10, 16	830	3156	1496
13	10, 16, 18	930	3056	1456
14	1, 7, 10, 16, 18	1125	2861	1396
15	1, 2, 7, 10, 16, 17, 18	1325	2661	1443
16	1, 2, 7, 10, 17, 18	1105	2881	1273
17	1, 2, 10, 17, 18	1010	2976	1263
18	1, 3, 10, 17	910	3076	1655
19	1, 3, 10, 17	910	3076	1695
20	3, 10, 20	930	3056	1675
21	10, 20	830	3156	1805
22	20	220	3766	1705
23	-	-	3986	1766
24	14	100	3886	1946
25	14, 21	340	3646	2116
26	14, 21	340	3646	1916

Table 6.20: 22-Unit system output summary (continued): Levelling the reserve

Week	*Units in maintenance*	*Capacity on maintenance*	*Available generation*	*Peak load*
27	14, 21	340	3646	1737
28	14, 22	340	3646	1927
29	14, 22	340	3646	2137
30	22	240	3746	1927
31	8, 11, 22	431	3555	1907
32	8, 11, 22	431	3555	1888
33	8, 11, 19	411	3575	1818
34	8, 11, 13, 19	511	3475	1848
35	13, 19	320	3666	2118
36	13	100	3866	1870
37	-	-	3986	2089
38	-	-	3986	1989
39	9	650	3336	1999
40	9	650	3336	1982
41	5, 9	740	3246	1672
42	5, 9	740	3246	1782
43	5, 9	740	3246	1772
44	5	90	3896	1556
45	5	90	3896	1706
46	6	90	3896	1806
47	6	90	3896	1826
48	6	90	3896	1906
49	4, 6	190	3796	1999
50	4	100	3886	2109
51	4	100	3886	2209
52	-	-	3986	1779

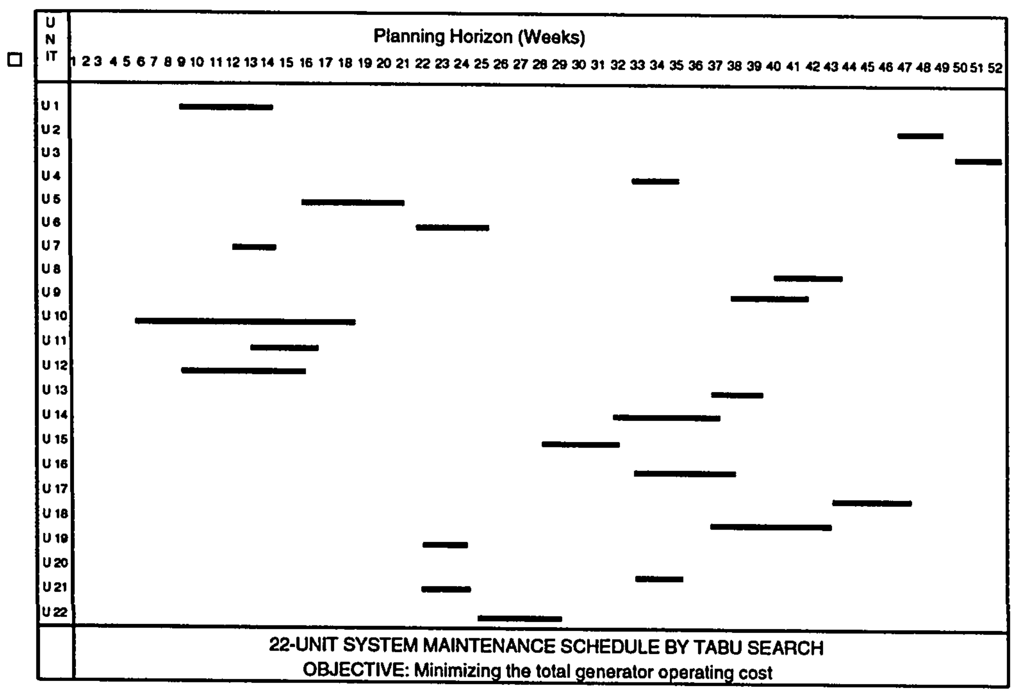

Figure 6.10: 22-unit maintenance schedule by Tabu search: Minimizing total generator operating cost

Table 6.21: 22-Unit system maintenance schedule (minimizing total generator operating cost) by tabu search

Unit	M_i	*MSP*	*Weeks in maintenance*
1	6	9	9, 10, 11, 12, 13, 14
2	3	47	47, 48, 49
3	3	50	50, 51, 52
4	3	33	33, 34, 35
5	6	16	16, 17, 18, 19, 20, 21
6	4	22	22, 23, 24, 25
7	3	12	12, 13, 14
8	4	40	40, 41, 42, 43
9	5	38	38, 39, 40, 41, 42
10	12	6	6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17
11	4	13	13, 14, 15, 16
12	8	9	9, 10, 11, 12, 13, 14, 15, 16
13	3	37	37, 38, 39
14	6	32	32, 33, 34, 35, 36, 37
15	5	28	28, 29, 30, 31, 32
16	6	33	33, 34, 35, 36, 37, 38
17	5	43	43, 44, 45, 46, 47
18	5	37	37, 38, 39, 40, 41
19	3	22	22, 23, 24
20	3	33	33, 34, 35
21	3	22	22, 23, 24
22	5	25	25, 26, 27, 28, 29

Table 6.22: 22-Unit system output summary: Minimizing total generating operating cost

Week	*Units in maintenance*	*Capacity on maintenance*	*Available generation*	*Peak load*
1	-	-	3986	1694
2	-	-	3986	1714
3	-	-	3986	1844
4	-	-	3986	1694
5	-	-	3986	1684
6	10	610	3376	1763
7	10	610	3376	1663
8	10	610	3376	1583
9	1, 10, 12	810	3176	1543
10	1, 10, 12	810	3176	1586
11	1, 10, 12	810	3176	1690
12	1, 7, 10, 12	905	3081	1496
13	1, 7, 10, 11, 12	996	2990	1456
14	1, 7, 10, 11, 12	996	2990	1396
15	10, 11, 12	801	3185	1443
16	5, 10, 11, 12	891	3095	1273
17	5, 10	700	3286	1263
18	5	90	3986	1655
19	5	90	3986	1695
20	5	90	3986	1675
21	5	90	3986	1805
22	6, 19, 21	550	3436	1705
23	6, 19, 21	550	3436	1766
24	6, 19, 21	550	3436	1946
25	6, 22	330	3656	2116
26	22	240	3746	1916

Table 6.23: 22-Unit system output summary (continued): Minimizing the total generating operating cost

Week	*Units in maintenance*	*Capacity on maintenance*	*Available generation*	*Peak load*
27	22	240	3746	1737
28	15, 22	460	3526	1927
29	15, 22	460	3526	2137
30	15	220	3766	1927
31	15	220	3766	1907
32	14, 15	320	3666	1888
33	4, 14, 16	420	3566	1818
34	4, 14, 16	420	3566	1848
35	4, 14, 16	420	3566	2118
36	14, 16	320	3666	1870
37	13, 14, 16, 18	520	3466	2089
38	9, 13, 16, 18	1070	2916	1989
39	9, 13, 18	850	3136	1999
40	8, 9, 18	850	3136	1982
41	8, 9, 18	850	3136	1672
42	8, 9	750	3236	1782
43	8, 17	200	3786	1772
44	17	100	3886	1556
45	17	100	3886	1706
46	17	100	3886	1806
47	2, 17	200	3786	1826
48	2	100	3886	1906
49	2	100	3886	1999
50	3	100	3886	2109
51	3	100	3886	2209
52	3	100	3886	1779

6.5 Comparison with published results

The test systems considered for simulation in this work were earlier used by researchers for maintenance scheduling purposes. In [16], the 4-unit and the 22-unit systems were used. The constraints considered were the resource, crew and precedence constraints. The maintenance scheduling optimization was carried out for different objective criteria such as minimizing the maintenance beginning cost-preference function, maximizing the minimum net reserve etc. The maintenance schedules that were obtained for these objective criteria are very close to the ones obtained in this work. For example, the 4-unit system has a maintenance schedule of (1, 1, 5, 3). The schedule obtained in this work for the objective criterion levelling the reserve is (1, 1, 5, 7). It can thus be seen that only the maintenance start period of the fourth unit is different.

In [20], the 5-unit system was used. The planning horizon considered was 12 weeks. (7, 10, 3, 1, 5) was the schedule that was obtained. In [31], the schedule obtained for the 10-unit system is (3, 10, 5, 1, 12, 9, 3, 4, 6, 7). This schedule is summarized in Table. 6.24. Although these schedules were obtained for different objective criteria, they are comparable to the maintenance schedules obtained in the present work.

Table 6.24: 10-Unit system maintenance schedule (ref: 31).

i	R_i	M_i $(months)$	MSP
1	1000	2	3
2	1000	2	10
3	800	1	5
4	800	2	1
5	500	1	12
6	500	1	9
7	300	1	3
8	200	1	4
9	100	1	6
10	100	1	7

Table 6.25: 22-Unit system maintenance schedule (ref: 16).

i	R_i	M_i	MSP
1	100	6	18
2	100	3	31
3	100	3	38
4	100	3	46
5	90	6	24
6	90	4	20
7	95	3	17
8	100	4	30
9	650	5	41
10	610	12	6
11	91	4	4
12	100	8	30
13	100	3	49
14	100	6	38
15	220	5	19
16	220	6	24
17	100	5	8
18	100	5	44
19	220	3	16
20	220	3	13
21	240	3	46
22	240	5	1

Chapter 7

Conclusions and Future Work

This short chapter concludes the thesis and highlights some future work.

7.1 Conclusions

An improved optimization model has been developed for the purpose of scheduling generating units in a power system for maintenance. A feature of this model is the ease in which complex constraints such as maintenance completion, crew, precedence, resource and reserve constraints can be formulated. This model can be solved using optimization techniques such as zero-one integer programming and tabu search.

Maintenance scheduling is a large-scale combinatorial optimization problem. Using exact solution techniques such as zero-one integer programming will place an undue burden on the computing resources (storage & time). Therefore it is preferable to use heuristic techniques to solve the maintenance scheduling optimization problem.

Tabu search is a promising and a powerful heuristic optimization technique. It is easy to implement, may escape local minima and also cope with large-scale problems involving complex constraints. In this thesis, the tabu search strategy has been implemented for scheduling generators for maintenance in a power system. Two objectives namely levelling the reserve and minimizing the total generator operating costs were separately considered. Investigation was done in finding a good initial solution to start with, generation of neighborhood solutions, formulation and maintenance of tabu lists, finding the right tabu list sizes and defining proper aspiration and stopping criteria. Relative to the dimension of the maintenance scheduling problem, comparable results have been obtained in low execution times. The efficacy of the tabu search technique will be apparent when scheduling large number of generators and when rapid revisions of maintenance schedules are required.

7.2 Future work

The maintenance scheduling model used in the present work is a deterministic model. A probabilistic model which incorporates uncertainties in the load demand, availability of spare parts etc can be further developed.

The effectiveness of tabu search as a control mechanism to direct other optimization techniques such as simulated annealing can be investigated. The combination of tabu search and simulated annealing would give rise to hybrid algorithms that might form the basis for approaching the maintenance scheduling problem in a more effective manner. Further, studies can be undertaken to investigate the merits and applicability of the genetic algorithm technique for solving the maintenance scheduling problem.

Appendix

Equal Incremental cost method

The power output of unit i in period t, p_{it} is computed using the Equal Incremental cost method [32]. The units in production in period t are made to satisfy the peak load that exists in that period (week). The generator outputs are then used to compute the individual generation costs respectively.

Let,

D : forecasted peak load demand (MW) in any scheduling period t.

f_i : fuel cost for unit i ($\$/Btu$)

H_i : Btu per hour heat input for unit i (Mbtu/hr).

F_i : generation cost for unit i in period t ($/hr).

$$F_i = f_i H_i$$

F_T : Total generation cost.

λ : equal incremental cost ($/MWh).

If transmission losses are neglected, the total load demand in period t is related to the generation in the period t by the simple equality

$$\sum_{i=1}^{I} p_i = D$$

The cost associated with the total generation is given by

$$F_T = F_1(p_1) + \ldots\ldots + F_i(p_i)$$

where as an approximation

$$F_i(p_i) = a_i + b_i p_i + c_i p_i^2 \ \$/hr.$$

If one assumes that generation limits are not violated, we have for optimal generation in period t the following conditions.

$$L = \sum_{i=1}^{I} F_i(p_i) + \lambda(D - \sum_{i=1}^{I} p_i)$$

Setting the derivatives of the lagrangian with respect to p_i and λ to zero we obtain

$$0 = \frac{\partial L}{\partial p_i} = \frac{\partial F_i}{\partial p_i} - \lambda$$

$$0 = \frac{\partial L}{\partial \lambda} = D - \sum_{i=1}^{I} p_i$$

The derivatives $\frac{\partial F_i}{\partial p_i}$, $i = 1, \ldots, I$ are known as the *incremental costs* of the i *th* generator. From a physical point of view the incremental cost represents the cost (in \$/MWh) of generating the next MWh at the generation level of p_i.

From the above necessary optimality conditions it is clear that at the optimal levels of generation one has

$$\lambda = \frac{\partial F_i}{\partial p_i} \quad i = 1, \ldots, I$$

Solving for p_i in terms of λ, one obtains

$$\lambda = \frac{\partial F_i}{\partial p_i} = b_i + 2c_i p_i$$

Hence

$$p_i = \frac{(\lambda - b_i)}{2c_i}$$

Using the original equality constraint,

$$D = \sum_{i=1}^{I} p_i = \sum_{i=1}^{I} \frac{(\lambda - b_i)}{2c_i}$$

$$D = \alpha\lambda - \beta$$

where

$$\alpha = \sum_{i=1}^{I} \frac{1}{2c_i}; \qquad \beta = \sum_{i=1}^{I} \frac{b_i}{2c_i}$$

Thus,

$$\lambda = \frac{1}{\alpha}(D + \beta)$$

$$p_i = \frac{1}{2c_i}\left(\frac{1}{\alpha}(D + \beta) - b_i\right)$$

Thus in the lossless case, the optimal levels of generation can be computed in a closed form fashion. At those levels they all have equal incremental cost.

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